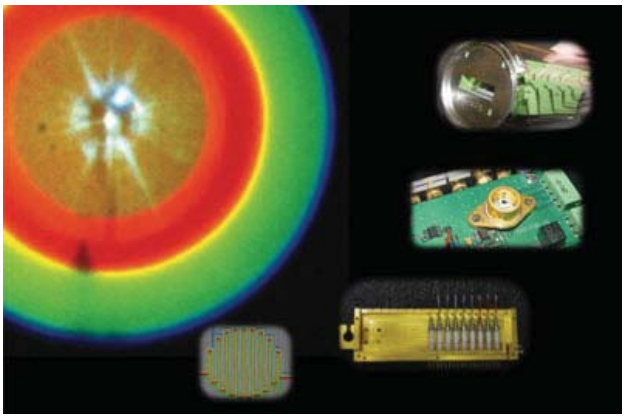

From Single-Photon to Multi-photon Metrology

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NIST, Boulder & Gaithersburg

1st NASA Quantum Future Technologies Conf., NASA Ames, CA , Jan. 19, 2012

Physical Measurement Laboratory

Abstract

- The significant potential of quantum information applications has been a real driver of single-photon source and detector development with sources based on phenomena ranging from nonlinear optics, to single isolated quantum systems, to atomic ensembles. Detector development is being pushed through semiconductor engineering, electronic control, signal processing, and new cryogenic-based schemes that provide high speed and photon-number-resolving capability. These schemes, as well as numerous others, are pushing the single-photon capability far beyond what has been possible in the past.

- The potential of this new capability has not gone unnoticed in the measurement community for new and higher accuracy measurement and metrology applications. Measurement applications that take advantage of nonclassical photon sources and detectors include Heisenberg-limited interferometry where n-photon states and n-photon detection can provide enhanced resolution and sensitivity relative to their classical counterparts, and other schemes that may even go beyond Heisenberg-limited interferometry. In the field of metrology there has been much interest in how to use this developing single-photon technology to push beyond existing limits of radiometry, which is currently the metrology field with the least accurately determined fundamental standards and the ties to measurements out of a metrology laboratory are also much poorer accuracy than such measurements tied to other standards. Given this current state of radiometric measurements and the rapid pace of the single-photon field there is a hope that these single-photon tools will provide a path toward much better radiometric measurements.

- One of the bases of this hope is that single-photon detectors and sources may provide a way to turn present analog radiometric measurements into a counting problem, which typically offers terrific measurement accuracy. That is for example, if a source can be created to provide a large but countable number of photons, or if a detector could count a similar number of photons, then currently analog measurements, become digital. While such capability should certainly be expected to provide advances in radiometry, there are issues that must be addressed. In particular this includes the efficiency with which such sources and detectors can be made to operate. This problem is one of the most difficult issues in this field and is the same issue that is largely responsible for existing radiometry measurement issues. Only time will tell whether this and other relevant issues can be successfully addressed, but given the significant advances and potential of single-photon devices it is a worthwhile pursuit and likely to provide many beneficial spinoffs on the road to that long term goal. We discuss the possibilities our hopes and concerns.

Outline

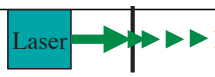
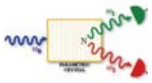
Problem: N-photon state metrology

How well we do with single photons

Then moving on to multi-photons

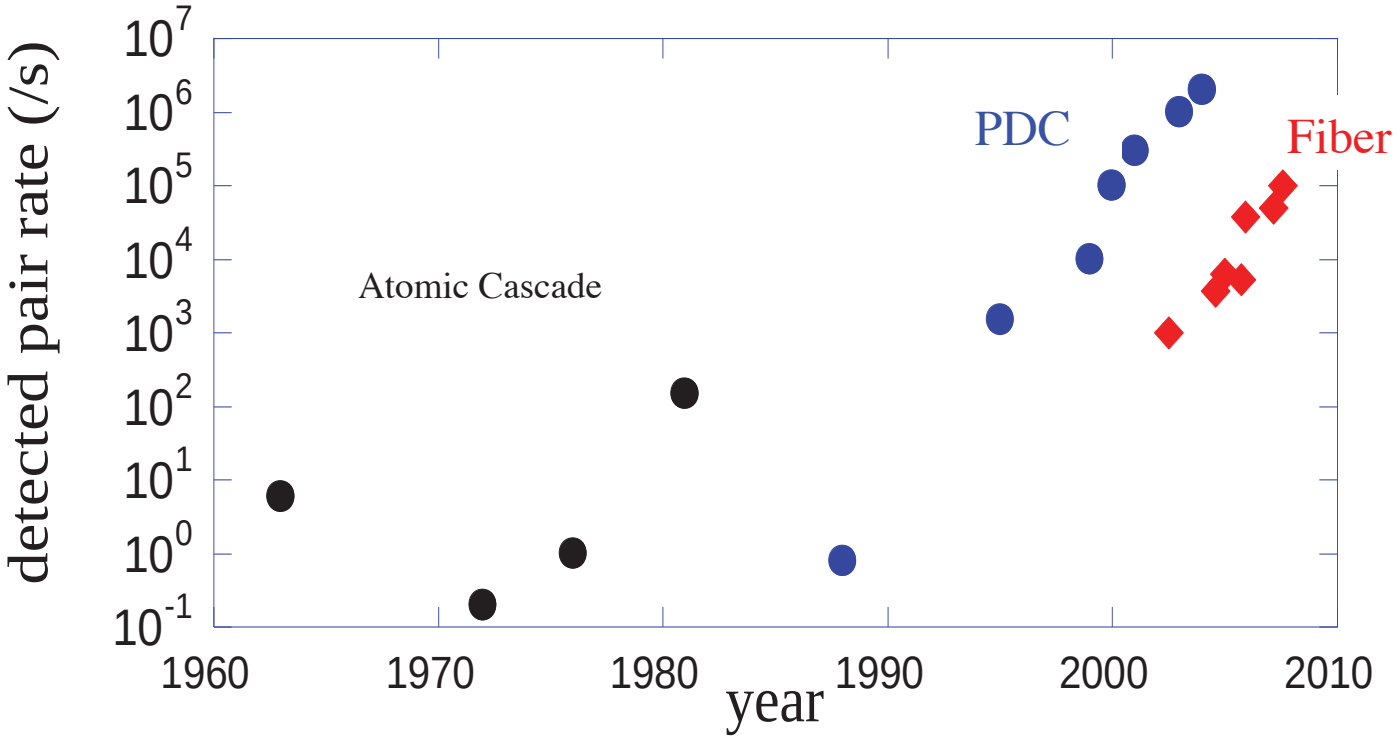
- Single Photon Tools
- Radiometry
  - Existing Standards- wholesale
  - Radiometry is hard
  - Single Photon Radiometry- retail
- Pushing the limits of Single Photon Tools

Sources

Source type	Prob. or Deter.	Temp. (K)	Wave-length range general	Wave-length tunability specific	Inherent bandwidth	Emission efficiency (Extraction)
Faint laser 	P	300	vis-IR	nm	GHz	1
Two photon (heralded)						
Atomic cascade	P	...	Atomic line	MHz	10 MHz	0.0001
PDC 						
Bulk	P	300	vis-IR	nm	nm	0.6
Periodically poled	P	300–400	vis-IR	nm	nm	0.85
Waveguide (periodically poled)	P	300–400	vis-IR	nm	nm	0.07
Gated	D	300	vis-IR	nm	nm	0.27
Multiplexed	D	300	vis-IR	nm	nm	0.1
FWM						
DSF	P	4–300	IR	nm	nm	0.02
BSMF	P	300	vis-IR	nm	nm	0.26
PCF	P	300	vis-IR	10 nm	nm	0.18
SOI waveguide	P	300	IR	10 nm	nm	0.17
Laser-PDC hybrid	P	300	vis-IR	nm	nm	...
Isolated system						
Single molecule	D	300	500–750 nm	30 nm	30 nm	0.04
Color center (NV)	D	300	640–800 nm	nm	nm	0.022
QD (GaN)	D	200	340–370 nm	nm	nm	...
QD (CdSe/ZnS)	D	300	500–900 nm	nm	15 nm	0.05
QD (InAs) in cavity	D	5	920–950 nm	10 GHz	1 GHz	0.1
Single ion in cavity	D	≈0	Atomic line	MHz	5 MHz	0.08
Single atom in cavity	D	≈0	Atomic line	MHz	10 MHz	0.05
Ensemble						
Rb, Cs	D	10^{-4}	Atomic line	MHz	10 MHz	0.2

Progress of Single Photon Sources

(limited by detector saturation)



Single Photon Detectors

η >50%

Detector Type	Operation Temp. (K)	Detection Efficiency, Wavelength $\eta(\%)$, λ (nm)	Timing Jitter, δt(ns) (FWHM)	Dark-count Rate, D (ungated) (1/s)	Figure of Merit	Max. Count Rate ($10^6/s$)	PNR Capability
PMT (visible–near-infrared) [271, 272]	300	40 @ 500	0.3	100	1.3×10^7	10	some
PMT (infrared) [273]	200	2 @ 1550	0.3	200000	3.3×10^2	10	some
Si SPAD (thick junction) [274]	250	65 @ 650	0.4	25	6.5×10^7	10	none
Si SPAD (shallow junction) [275]	250	49 @ 550	0.035	25	5.6×10^8	10	none
Si SPAD (self-differencing) [276]	250	74 @ 600	–	2000	–	16	some
Si SPAD (linear-mode) [277]	78	56 @ 450	–	0.0008	–	0.01	full*
Si SPAD (cavity) [278]	78	42 @ 780	0.035	3500	3.4×10^6	10	none
Si SPAD (multipixel) [279, 280]	290	40 @ 532	0.3	25000-500000	1×10^4	30	some
Hybrid PMT (PMT + APD) [281, 282]	270	30 @ 1064	0.2	30000	5×10^4	200	none
Time multiplexed (Si SPAD) [234]	250	39 @ 680	0.4	200	5×10^6	0.5	some
Time multiplexed (Si SPAD) [283]	250	50 @ 825	0.5	150	7×10^6	2	some
Space multiplexed (InGaAs SPAD) [284]	250	33 @ 1060	0.133	160000000	1.6×10^1	10	some
Space multiplexed (InGaAs SPAD) [285]	250	2 @ 1550	–	–	–	0.3	none
InGaAs SPAD (gated) [286]	200	10 @ 1550	0.370	91	3.0×10^5	0.01	none
InGaAs SPAD (self-differencing) [287]	240	10 @ 1550	0.055	16000	1.1×10^5	100	none
InGaAs SPAD (self-differencing) [267]	240	10 @ 1550	–	–	–	–	full
InGaAs SPAD (discharge pulse counting) [288]	243	7 @ 1550	–	40000	–	10	none
InP NFAD (monolithic negative feedback) [289, 290]	243	6 @ 1550	0.4	28000	–	10	some
InGaAs (self-quenching & self-recovery) [291]	300	– @ 1550	10	–	–	3	some
CIPD (InGaAs) [263]	4.2	80 @ 1310	–	–	–	0.001	full
Frequency up-conversion [292]	300	8.8 @ 1550	0.4	13000	1.7×10^4	10	none
Frequency up-conversion [254, 293]	300	56-59@ 1550	–	460000	–	5	none
Frequency up-conversion [294]	300	20 @ 1306	0.62	2200	1.5×10^5	10	none
VLPC [295]	7	88 @ 694	40	20000	1.1×10^3	10	some
VLPC [296]	7	40 @ 633	0.24	25000	6.7×10^4	10	some
SSPM [297]	6	76 @ 702	3.5	7000	3×10^4	30	full
TES(W) [298]	0.1	50 @ 1550	100	3	1.7×10^6	0.1	full
TES(W) [299]	0.1	95 @ 1556	100	–	–	0.1	full
TES(Ha) [300]	0.1	85 @ 850	100	–	–	0.1	full
TES (Ti) [301–303]	0.1	81-98 @ 850	100	–	–	1	full
SNSPD [304]	3	0.7 @ 1550	0.06	10	1.2×10^7	100	none
SNSPD (in cavity) [253]	1.5	57 @ 1550	0.03	–	–	1000	none
Parallel-SNSPD [262]	2	2 @ 1300	0.05	0.15	2.7×10^9	1000	some
STJ [258, 259, 305]	0.4	45 @ 350	2000	–	–	0.01	full
QD (resonant tunnel diode) [306]	4	12 @ 550	150	0.002	4×10^9	0.25	full
QDOGFET (field-effect transistor) [265, 307, 308]	4	2 @ 805	10000	150	10	0.05	full

>100 MHz

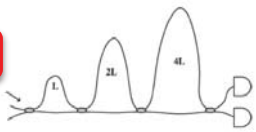
Detectors

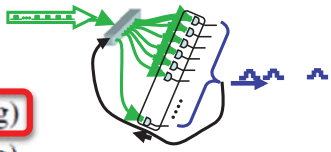
RSI Source & Detector Review **82**, 071101 (2011)

η >50%

>100 MHz

Detector type	Operation temperature (K)	Detection efficiency, wavelength η(%), λ (nm)	Timing jitter, δt(ns) (FWHM)	Dark-count rate, D (ungated) (1/s)	PNR
PMT (visible–near-infrared)	300	40 @ 500	0.3	100	some
PMT (infrared)	200	2 @ 1550	0.3	200 000	some
Si SPAD (thick junction)	250	65 @ 650	0.4	25	
(shallow junction)	250	49 @ 550	0.035	25	
(self-differencing)	250	74 @ 600	...	2000	
(linear mode)	78	56 @ 450	...	0.0008	full
(cavity)	78	42 @ 780	0.035	3500	
(multipixel)	290	40 @ 532	0.3	25 000–500 000	some
Hybrid PMT (PMT + APD)	270	30 @ 1064	0.2	30 000	
Time multiplexed (Si SPAD)	250	39 @ 680	0.4	200	some
(Si SPAD)	250	50 @ 825	0.5	150	some
Space multiplexed (InGaAs SPAD)	250	33 @ 1060	0.133	160 000 000	some
		2 @ 1550	...	...	
InGaAs SPAD (gated)		10 @ 1550	0.370	91	
(self-differencing)		10 @ 1550	0.055	16 000	
(self-differencing)	240	10 @ 1550	...	...	full
(discharge pulse counting)	243	7 @ 1550	...	40 000	
InP NFAD (monolithic negative feedback)	243	6 @ 1550	0.4	28 000	some





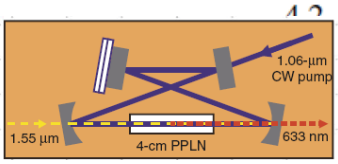
Detectors

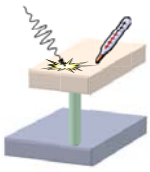
RSI Source & Detector Review **82**, 071101 (2011)

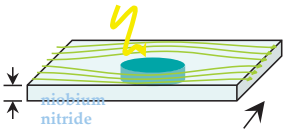
η >50%

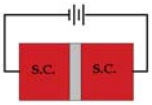
>100 MHz

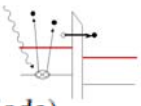
Detector type	Operation temperature (K)	Detection efficiency, wavelength η(%), λ (nm)	Timing jitter, δt(ns) (FWHM)	Dark-count rate, D (ungated) (1/s)	PNR
InGaAs (self-quenching and self-recovery)	300	... @ 1550	10	...	some
CIPD (InGaAs)	4.2	80 @ 1310	...	...	some
Frequency up-conversion		8.8 @ 1550	0.4	13000	
		56-59 @ 1550	...	460000	
		20 @ 1306	0.62	2200	
VLPC	7	88 @ 694	40	20000	some
	7	40 @ 633	0.24	25000	some
SSPM	6	76 @ 702	3.5	7000	full
TES(W)	0.1	50 @ 1550	100	3	full
	0.1	95 @ 1556	100	...	full
TES(Ha)	0.1	85 @ 850	100	...	full
TES (Ti)	0.1	81–98 @ 850	100	...	full
SNSPD	3	0.7 @ 1550	0.06	10	
SNSPD (in cavity)	1.5	57 @ 1550	0.03	...	
Parallel SNSPD	2	2 @ 1300	0.05	0.15	some
STJ	0.4	45 @ 350	2000	...	full
QD (resonant tunnel diode)	4	12 @ 550	150	0.002	full
QDOGFET (field-effect transistor)	4	2 @ 805	10000	150	full

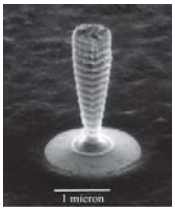












Single Photons to Conventional Radiometry Dynamic Range Efforts

Nuclear Instruments and Methods in Physics Research A 610 (2009) 183–187

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Providing reference standards and metrology for the few photon–photon counting community

Andrew R. Beaumont, Jessica Y. Cheung *, Christopher J. Chunnilall, Jane Ireland, Malcolm G. White

IOP Publishing — Metrologia

Metrologia **47** (2010) R33–R40 — doi:10.1088/0026-1394/47/5/R02

REVIEW ARTICLE

From single photons to milliwatt radiant power—electron storage rings as radiation sources with a high dynamic range

Roman Klein, Reiner Thornagel and Gerhard Ulm

Physikalisch-Technische Bundesanstalt, Abbestr. 2–12, 10587 Berlin, Germany

Single Photon Metrology at SWP 2011

- Gerrits: Extending Single-Photon Optimized Superconducting Transition Edge Sensors Beyond the Single-Photon Counting Regime
- Smith: Quantum-enhanced metrology in the real world: Losses, decoherence, and noise make life on the quantum edge challenging
- Müller: Towards Traceable Calibration of Single Photon Detectors Using Synchrotron Radiation
- Rastello: Metrology Towards Quantum-Based Photon Standards
- Porrovecchio: A transfer standard for the low power / few photon regime – the trap detector plus switched integrator amplifier
- Schmunk: Relative detection efficiency calibration of single photon avalanche photo detectors using non-classical light

Dynamic Range Effort

Traceability for single-photon sources

The development of highly efficient quantum light sources at the single photon level and the development of entanglement assisted measurement techniques would enable classical measurement limits to be overcome. These new traceable photon sources will underpin the growth of several emerging technologies, such as optical devices for quantum communication, computing, microscopy, nanosciences, nanofabrication and other new production technologies, as well as fundamental metrology.

Objectives:
Traceability for single-photon sources

The JRP shall focus on the traceable measurement and characterisation of source-based standards for photon metrology spanning the range 1 photon/s to 10^8 photons/s.

The specific objectives are:

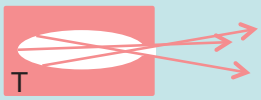
1. To develop absolute and calculable single photon sources with high dynamic range at both telecom and visible wavelengths.
2. To develop efficient single photon sources, to support for SI traceable photon radiometry.
3. To develop quantum optical state sources for entanglement enhanced measurements.
4. To develop optimised photon-coupling strategies and methods between source and detector.

The sources developed in objectives 1-3, should be characterised for photon flux, and by appropriate metrics in terms of statistics, anti-bunching, indistinguishability, degree of entanglement and sub-shot-noise as required by the application.

Radiometric Standards

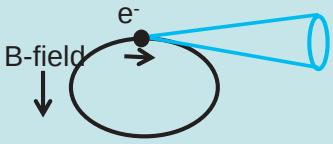
Sources

Blackbody



Temperature → Radiance

Synchrotron

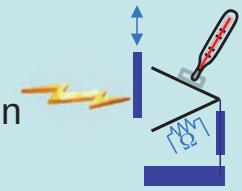


B-field, current, energy → Radiance

Detectors

Trap: Radiometer

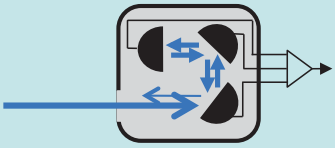
Electrical Substitution



Radiant power

Trap:

Semiconductor



Radiant power

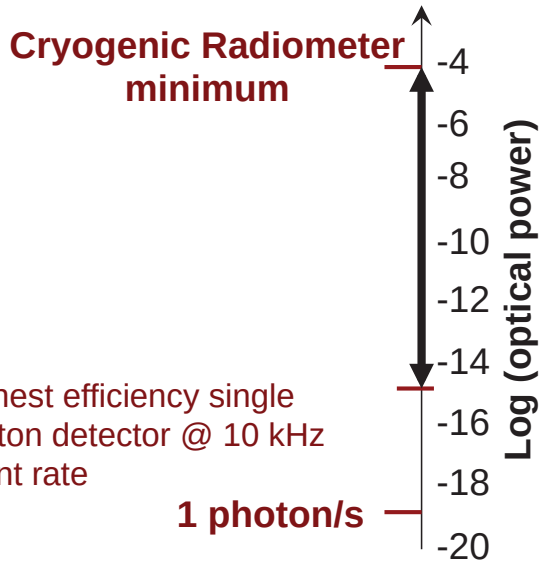
Single Photons?

The Issue

From best detector-based uncertainties and single photons:

- 15 order-of-magnitude range: Cryo-radiometry to Single Photon
- Standards are inherently not photon-counting

For λ = 1 μm photons
$E=2\times10^{-19}$ J

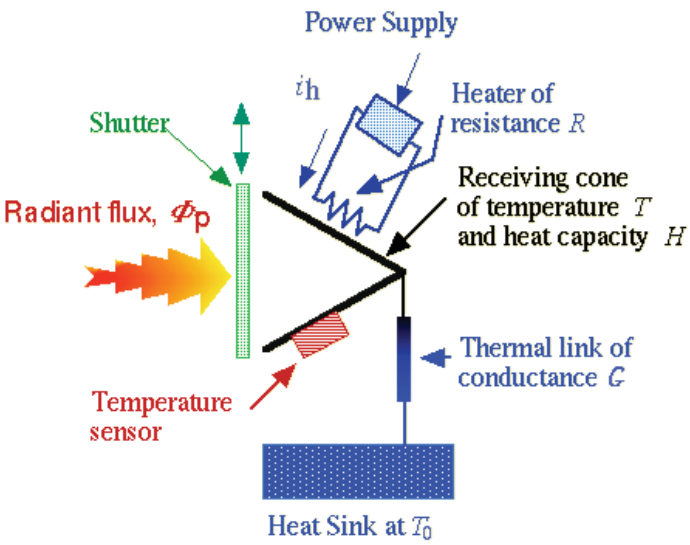


World's best radiometry
Uncert ~0.01% @ 0.1 mW

Long chain between conventional radiometry and photon counting

Radiometry

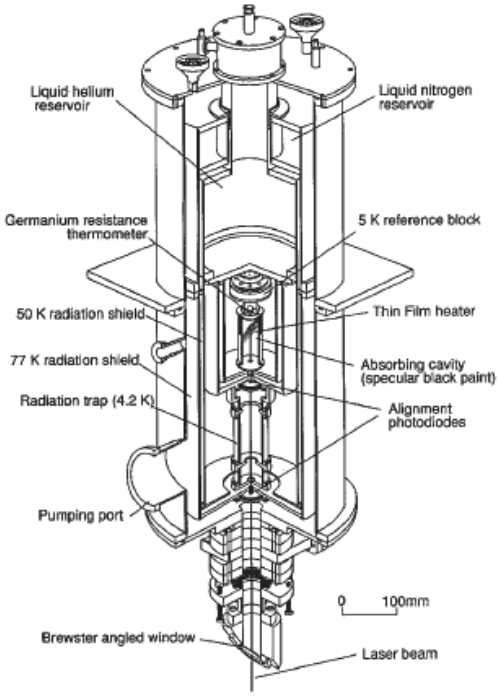
Electrical Substitution Radiometry



From NIST Technical Note 1421, A. Parr

Optical Power = Electrical Power

High-Accuracy Cryogenic Radiometer 1980s



Laser Optimized Cryogenic Radiometer 1990s

Cryogenic Radiometer Uncertainties

Table 1. Components of the Combined Relative Standard Uncertainty of 0.021% in the Measurement of Optical Power by the HACR[a]

Type	Typical Value of Correction	Component of Uncertainty (%)
Type A		0.010
Type B, combined		0.019
Window transmittance (T)	0.99970	0.016
Scattered optical power (P_S), nW	50	0.006
Cavity absorptance (A)	0.99998	0.002
Nonequivalence (N)	1.00000	
Power dependent		0.005
Temperature gradients		0.004
Heater power (P_H)		
V_H, V_R		0.003
R		0.0003

Getting the light in

National Institute of Standards and Technology high-accuracy cryogenic radiometer

T. R. Gentile, J. M. Houston, J. E. Hardis, C. L. Cromer, and A. C. Parr

1056 APPLIED OPTICS / Vol. 35, No. 7 / 1 March 1996

Radiometry is Hard

From: **http://physics.nist.gov/constants**

Fundamental Physical Constants — Frequently used constants

Quantity	Symbol	Value	Unit	Relative std. uncert. u_r
speed of light in vacuum	c, c_0	299 792 458	m s^{-1}	exact
magnetic constant	μ_0	$4\pi \times 10^{-7}$	N A^{-2}	
		$= 12.566\,370\,614... \times 10^{-7}$	N A^{-2}	exact
electric constant $1/\mu_0 c^2$	ϵ_0	$8.854\,187\,817... \times 10^{-12}$	F m^{-1}	exact
Newtonian constant of gravitation	G	$6.673\,84(80) \times 10^{-11}$	m^3 kg^{-1} s^{-2}	1.2×10^{-4}
Planck constant	h	$6.626\,069\,57(29) \times 10^{-34}$	J s	4.4×10^{-8}
$h/2\pi$	$\hbar$	$1.054\,571\,726(47) \times 10^{-34}$	J s	4.4×10^{-8}
elementary charge	e	$1.602\,176\,565(35) \times 10^{-19}$	C	2.2×10^{-8}
magnetic flux quantum $h/2e$	Φ_0	$2.067\,833\,758(46) \times 10^{-15}$	Wb	2.2×10^{-8}
conductance quantum $2e^2/h$	G_0	$7.748\,091\,7346(25) \times 10^{-5}$	S	3.2×10^{-10}
electron mass	m_e	$9.109\,382\,91(40) \times 10^{-31}$	kg	4.4×10^{-8}
proton mass	m_p	$1.672\,621\,777(74) \times 10^{-27}$	kg	4.4×10^{-8}
proton-electron mass ratio	m_p/m_e	$1836.152\,672\,45(75)$		4.1×10^{-10}
fine-structure constant $e^2/4\pi\epsilon_0\hbar c$	α	$7.297\,352\,5698(24) \times 10^{-3}$		3.2×10^{-10}
inverse fine-structure constant	α^{-1}	$137.035\,999\,074(44)$		3.2×10^{-10}
Rydberg constant $\alpha^2 m_e c/2h$	R_∞	$10\,973\,731.568\,539(55)$	m^{-1}	5.0×10^{-12}
Avogadro constant	N_A, L	$6.022\,141\,29(27) \times 10^{23}$	mol^{-1}	4.4×10^{-8}
Faraday constant $N_A e$	F	$96\,485.3365(21)$	C mol^{-1}	2.2×10^{-8}
molar gas constant	R	$8.314\,4621(75)$	J mol^{-1} K^{-1}	9.1×10^{-7}
Boltzmann constant R/N_A	k	$1.380\,6488(13) \times 10^{-23}$	J K^{-1}	9.1×10^{-7}
Stefan-Boltzmann constant $(\pi^2/60)k^4/\hbar^3 c^2$	σ	$5.670\,373(21) \times 10^{-8}$	W m^{-2} K^{-4}	3.6×10^{-6}
Non-SI units accepted for use with the SI				
electron volt (e/C) J	eV	$1.602\,176\,565(35) \times 10^{-19}$	J	2.2×10^{-8}
(unified) atomic mass unit $\frac{1}{12}m(^{12}\mathrm{C})$	u	$1.660\,538\,921(73) \times 10^{-27}$	kg	4.4×10^{-8}

1.3×10^{-4}

Quinn & Martin 85

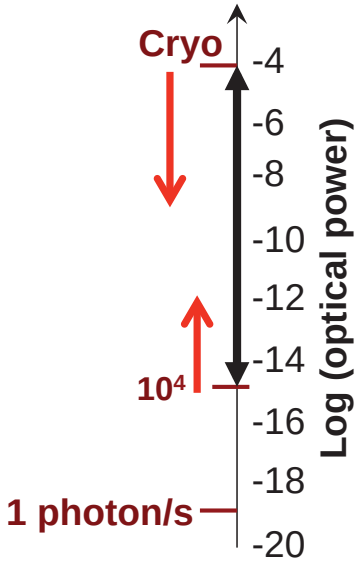
Opportunity: Closer Ties

- Reaching downwards to photon counting levels
  - Cryogenic radiometers
  - Transfers from Cryogenic radiometers
  - Source standards

- Reaching upwards to cryogenic radiometry levels
  - Single photon sources-

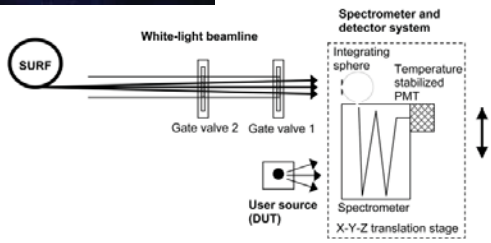
    countable single photon generation rates
  - Single photon detectors-

    countable single photon detection rates



Extending Source Dynamic Range Downward

Synchrotron linearity through
high dynamic range e^- beam current



IOP Publishing
Metrologia **47** (2010) R33–R40

REVIEW ARTICI

From single photons to milliwatt radiant power—electron storage rings as radiation sources with a high dynamic range

Roman Klein, Reiner Thornagel and Gerhard Ulm
Physikalisch-Technische Bundesanstalt, Abbestr. 2–12, 10587 Berlin, Germany

11-Decade Dynamic Range achieved
Radiant intensity uncertainty 0.03%*
*Not including: Window transmittance, bandwidth

Irradiance uncertainty 0.36%
Appl. Opt. **46** 25(2007)

Source linearity through
high dynamic range Optical Density

Transmittance measurements for filters of optical density between one and ten

Z. M. Zhang, T. R. Gentile, A. L. Migdall, and R. U. Datla

1 December 1997 / Vol. 36, No. 34 / APPLIED OPTICS 8889

OD=10 transmittance uncertainty=few %

Extending Detector Dynamic Range Downward

Si photodiode & amplifier

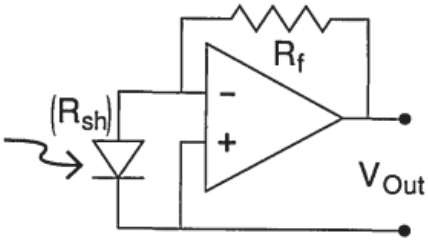
Noise= 800 photons/sec

with 400 s measurement times

Fourteen-decade photocurrent measurements with large-area silicon photodiodes at room temperature

Appl. Opt. 30 3091(1991)

G. Eppeldauer and J. E. Hardis



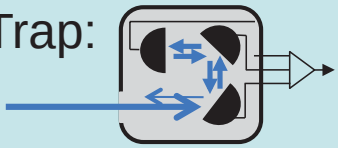
Low optical power reference detector implemented in the validation of two independent techniques for calibrating photon-counting detectors.

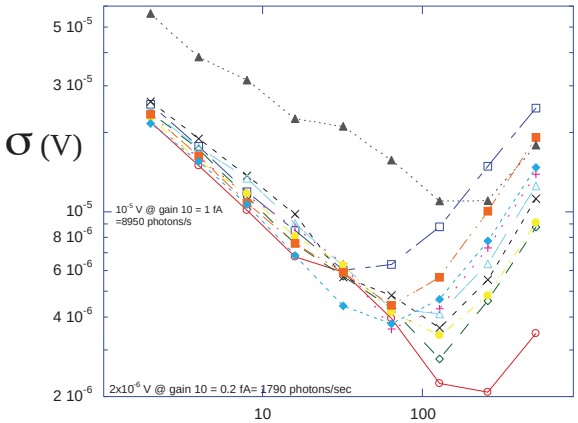
Opt. Expr. 19 20347(2011)

Jessica Y. Cheung,[1,*] Christopher J. Chunnilall,[1] Geiland Porrovecchio,[2] Marek Smid,[2] and Evangelos Theocharous[1]

Si Trap Detector:
$3x10^5$photons/s ±0.2% in 300s

Trap:





equivalent photon noise

9000 photon/s

1800 photon/s

Extending Cryogenic Radiometer Dynamic Range Downward

- Typical Cryo Radiometer-
  - max power 1 mW
  - Noise 3 nW
  - Absolute accuracy 0.005%

- NIST pW-ACR (Carter et al. Metrologia 2009)
  - Temp sensor: noncontact TES magnetization
  - Max power 20 nW
  - Noise1 fW
  - Absolute accuracy 0.1%

- Fiber radiometer

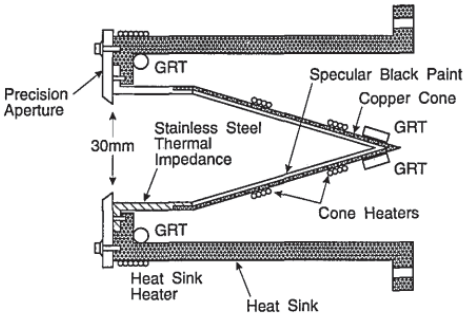


Fig. 5. ACR receiver subassembly.

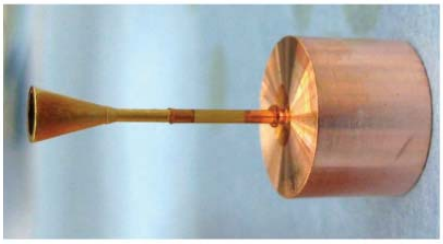
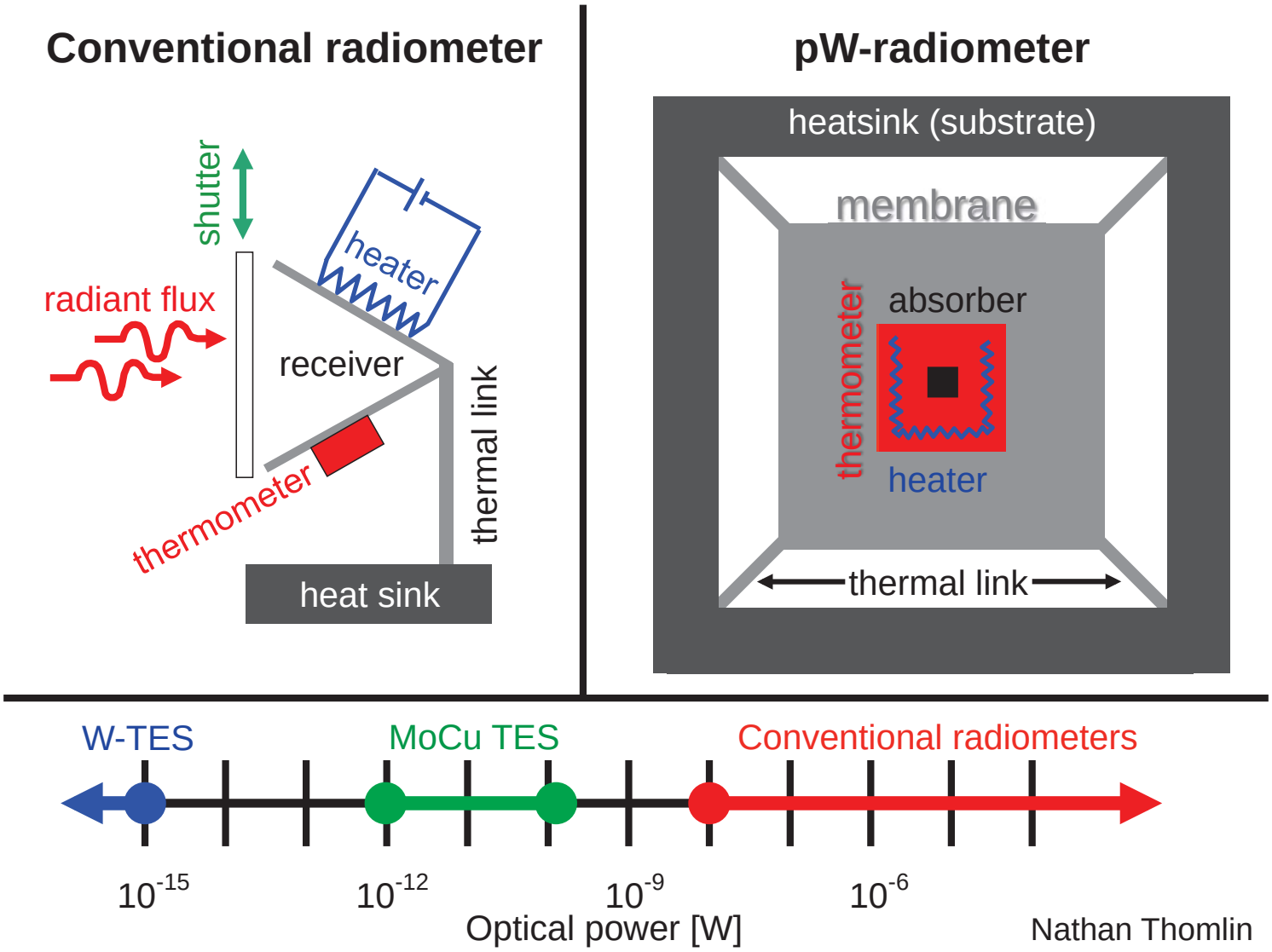
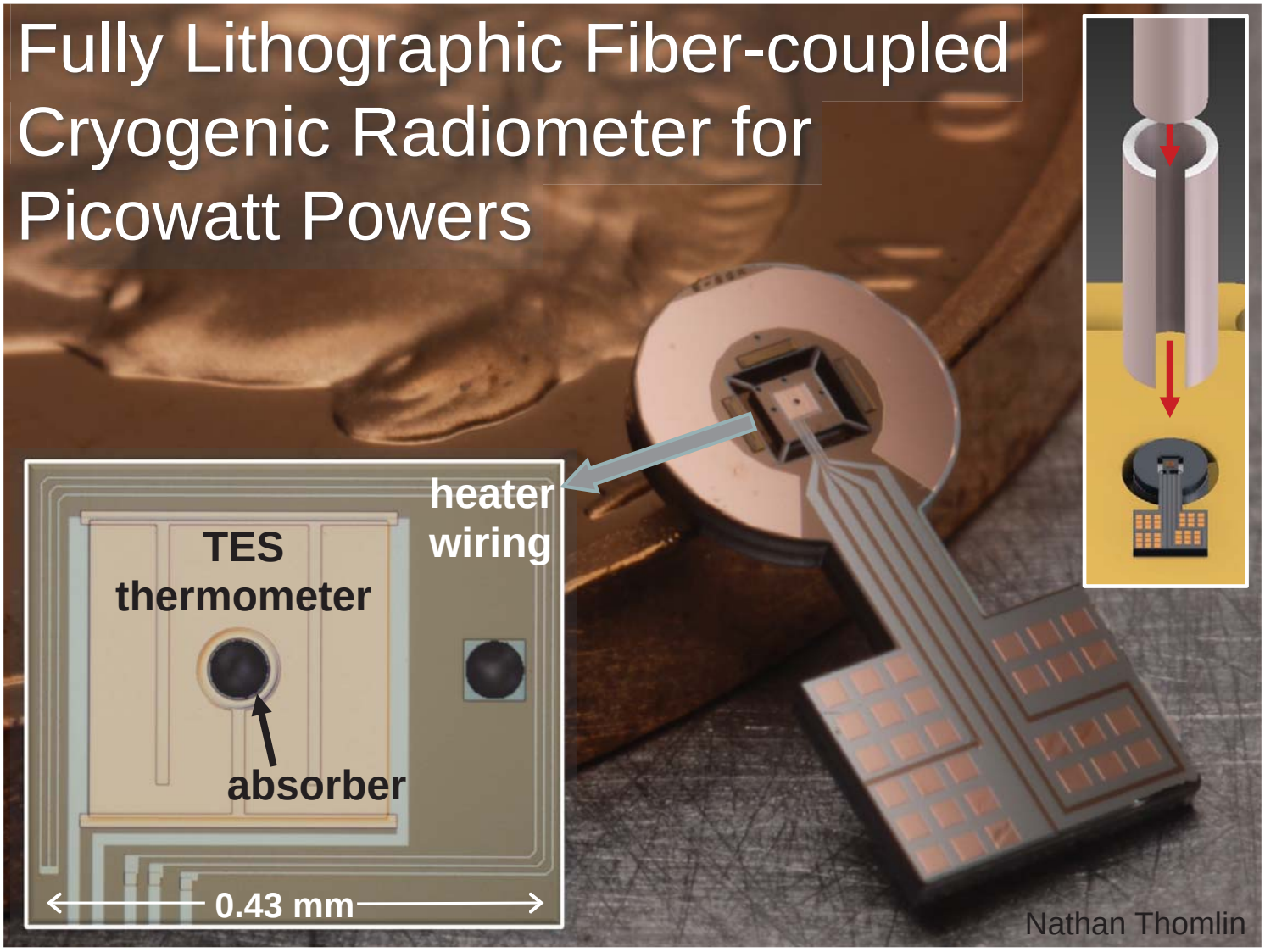


Figure 2. Photograph of a pW-ACR receiver cavity held in place by a thin Kapton tube. The receiver cone has a base diameter of 4 mm and is made from electroformed copper plated with gold. The Kapton has very low thermal conductance but is rigid enough to hold the cavity in place.

Table 1. Comparison of critical construction and performance parameters between the current ACRII and the planned pW-AC

Receiver cavity property	ACRII	pW-ACR
Cone angle/deg	30	30
Cone diameter/cm	2.5	0.4
Responsivity/K mW^{-1}	210	~30 000
Time constant/s	17	~50
Noise floor/pW	>8	~0.001
Maximum power/nW	$\sim 10^5$	~20


Conventional radiometer
shutter
heater
radiant flux
receiver
thermal link
thermometer
heat sink
pW-radiometer
heatsink (substrate)
membrane
absorber
thermometer
heater
thermal link
W-TES
MoCu TES
Conventional radiometers
10-15
10-12
10-9
10-6
Optical power [W]
Nathan Thomlin

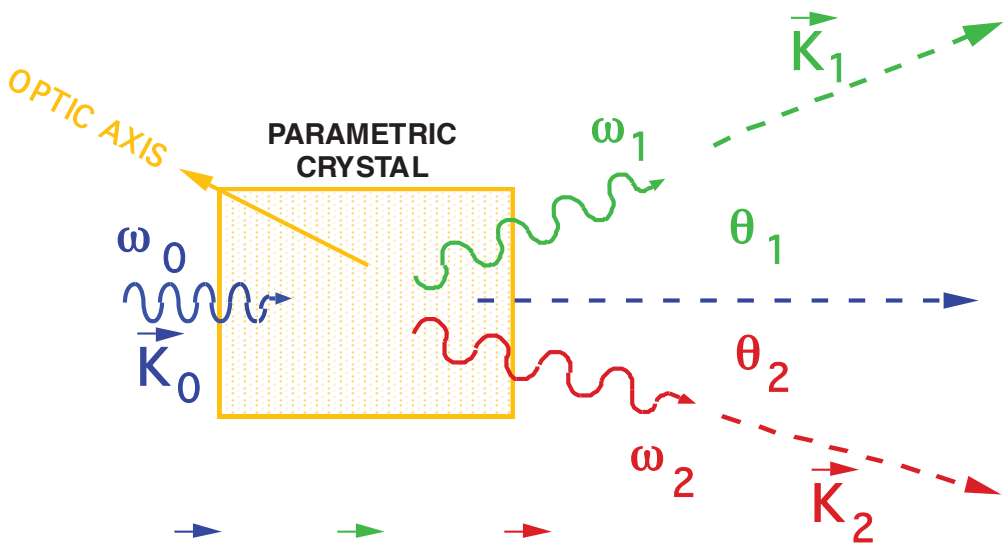

Fully Lithographic Fiber-coupled Cryogenic Radiometer for Picowatt Powers
heater wiring
TES thermometer
absorber
0.43 mm
Nathan Thomlin

Throwing Single Photon Tools at the Problem

Creating light two photons at a time

Optical Parametric Downconversion

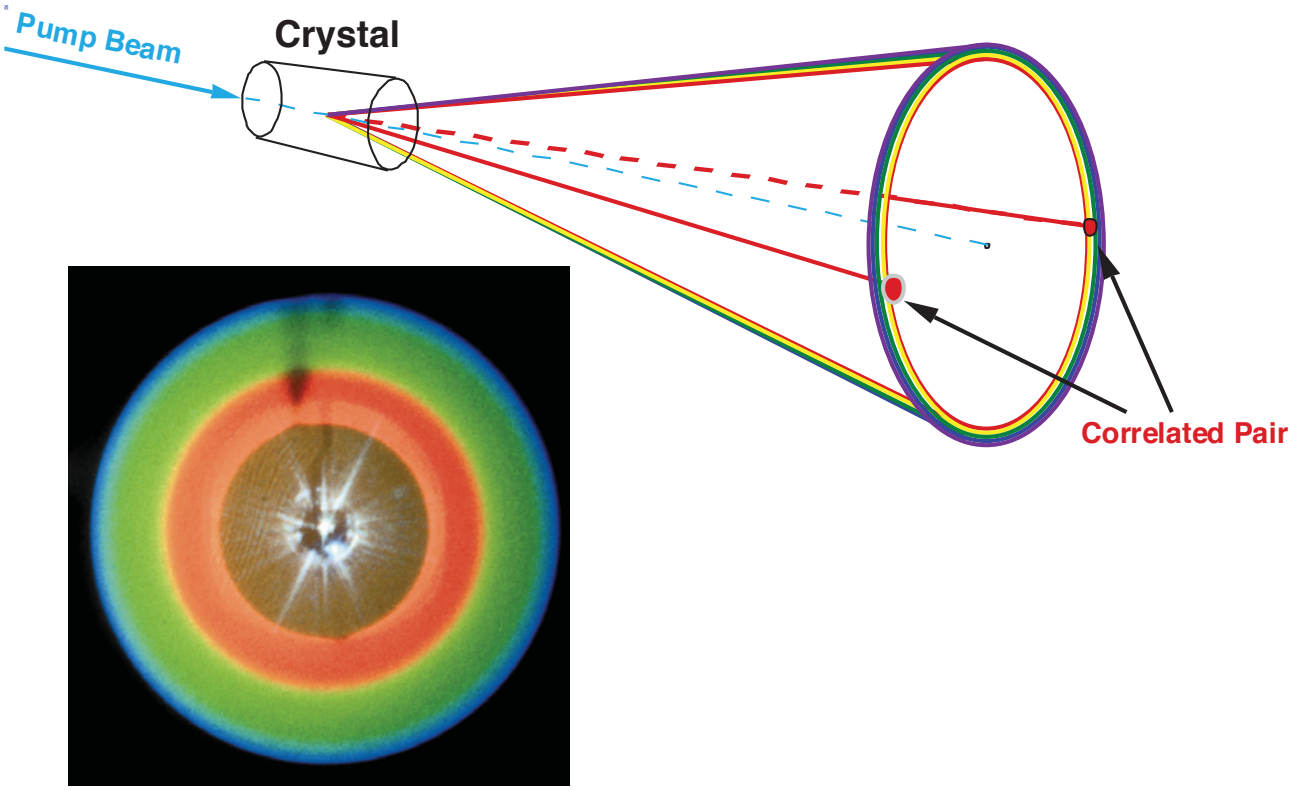
One in - two out

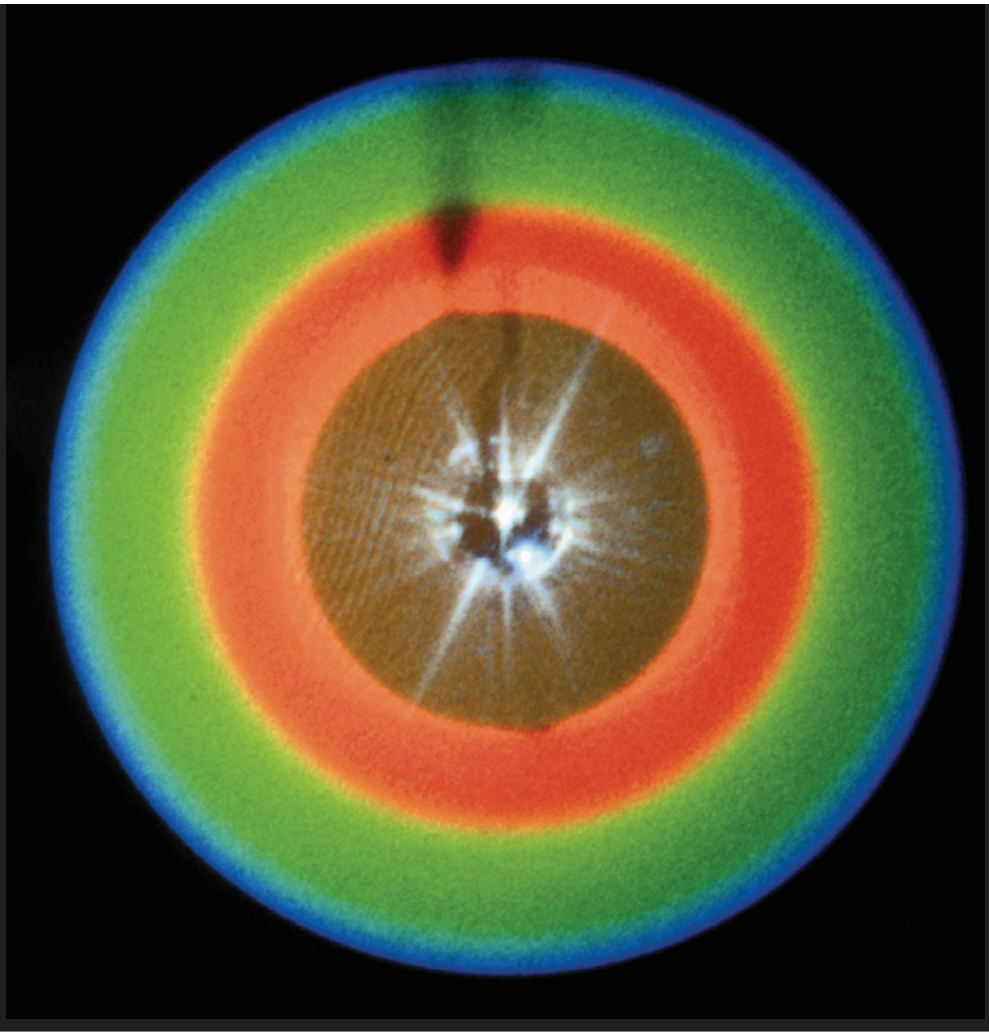


$$\vec{K}_0 = \vec{K}_1 + \vec{K}_2$$

$$\omega_0 = \omega_1 + \omega_2$$

Optical Parametric Downconversion

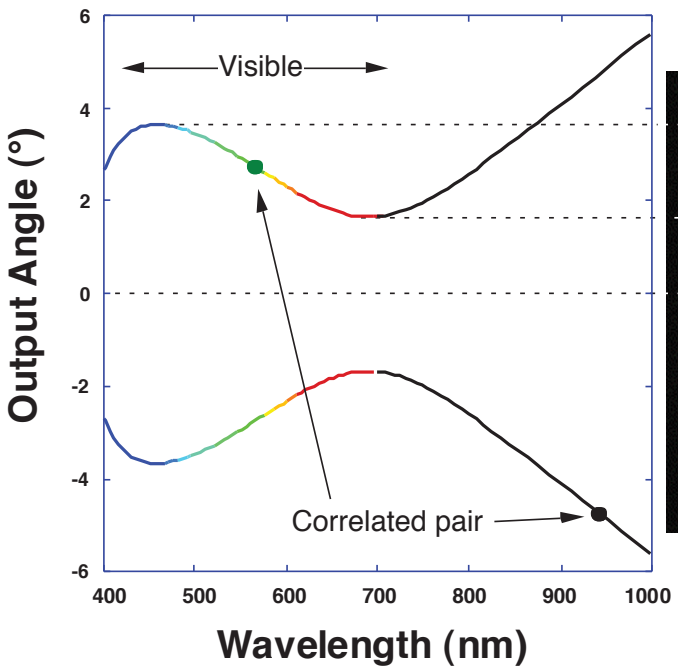


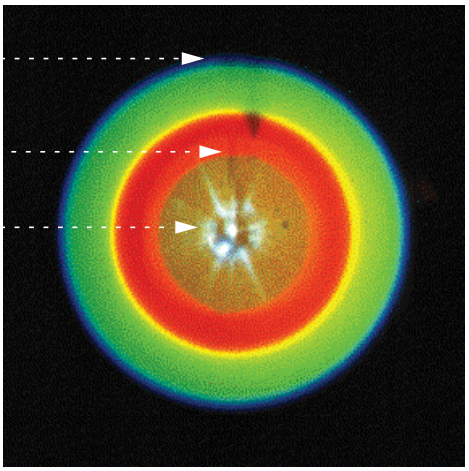


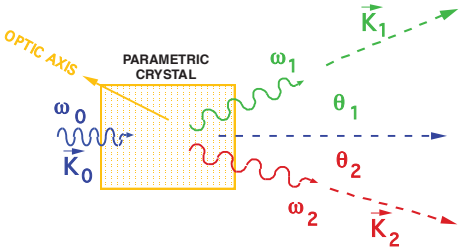
Two-photon light

- $\chi^{(2)}$ parametric down-conversion

  One photon in – two photons out

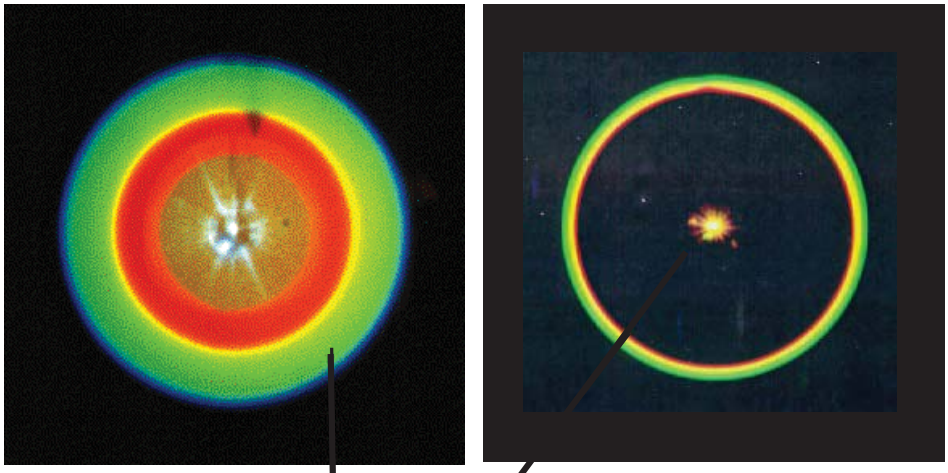


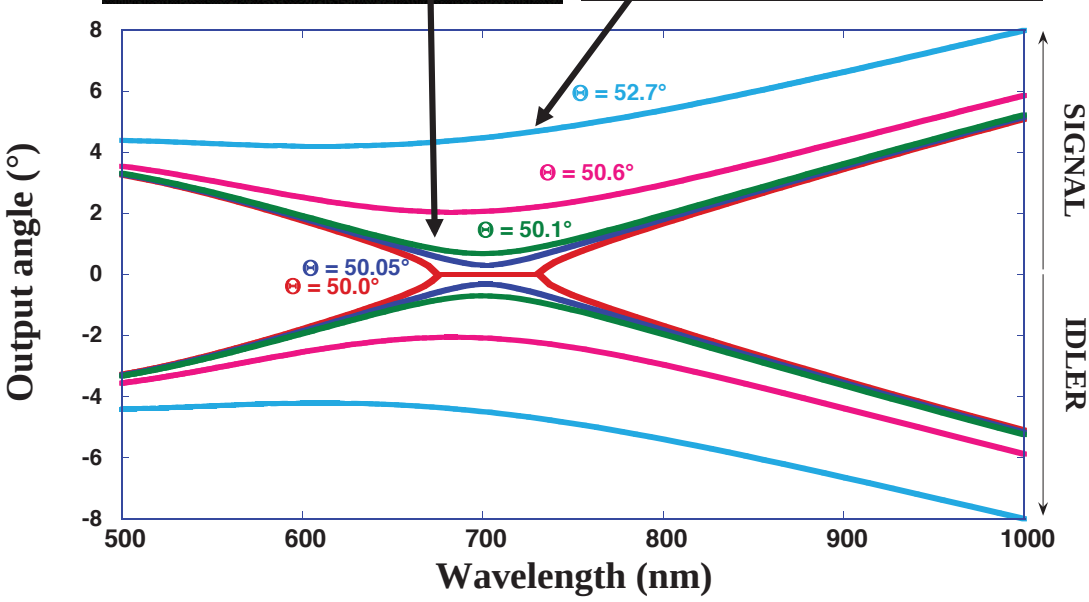




$\vec{K}_0 = \vec{K}_1 + \vec{K}_2 \qquad \omega_0 = \omega_1 + \omega_2$

Different Crystal Tilts Produce Different Output Patterns



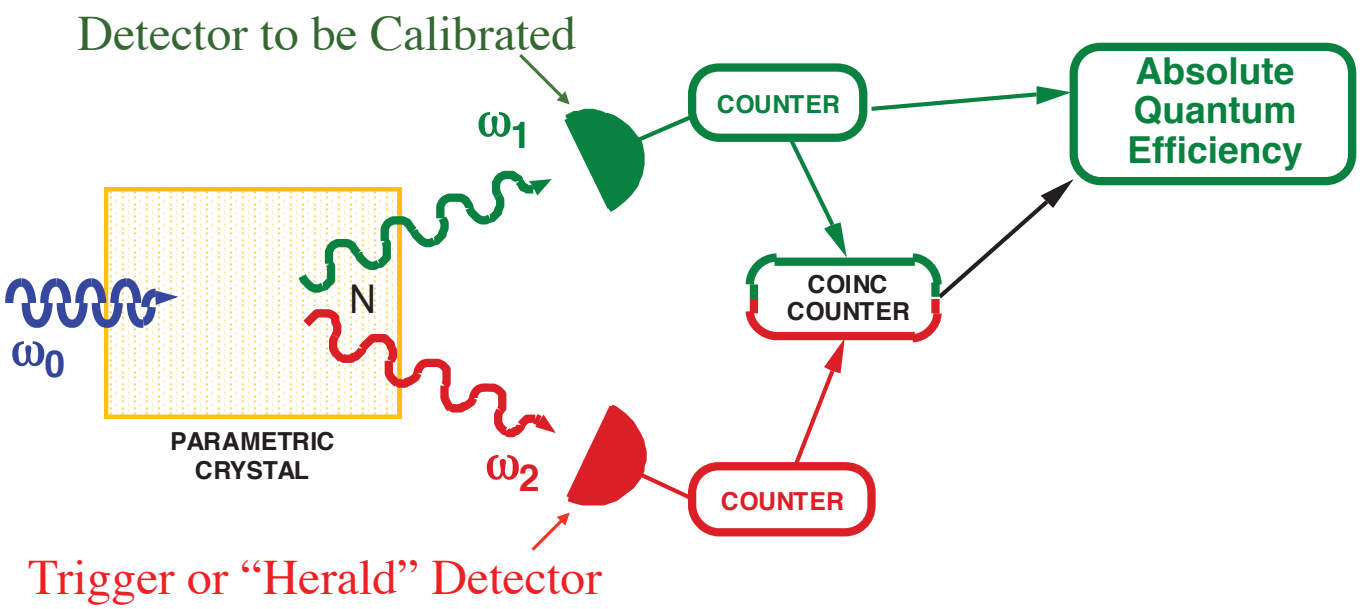


PDC displaying its own phase matching curve

Calc.

Two-Photon Detector Efficiency Metrology

No External Standards Needed!



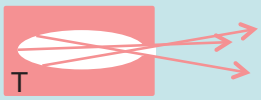
$N_1 = \eta_1 N$ $\quad N_2 = \eta_2 N$ $\quad N_C = \eta_1 \eta_2 N$

$$\eta_1 = N_C / N_2$$

Radiometric Standards

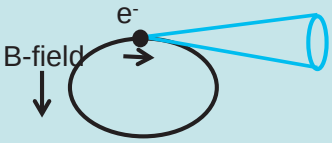
Sources

Blackbody



Temperature → Radiance

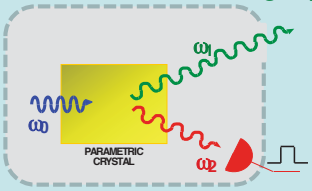
Synchrotron



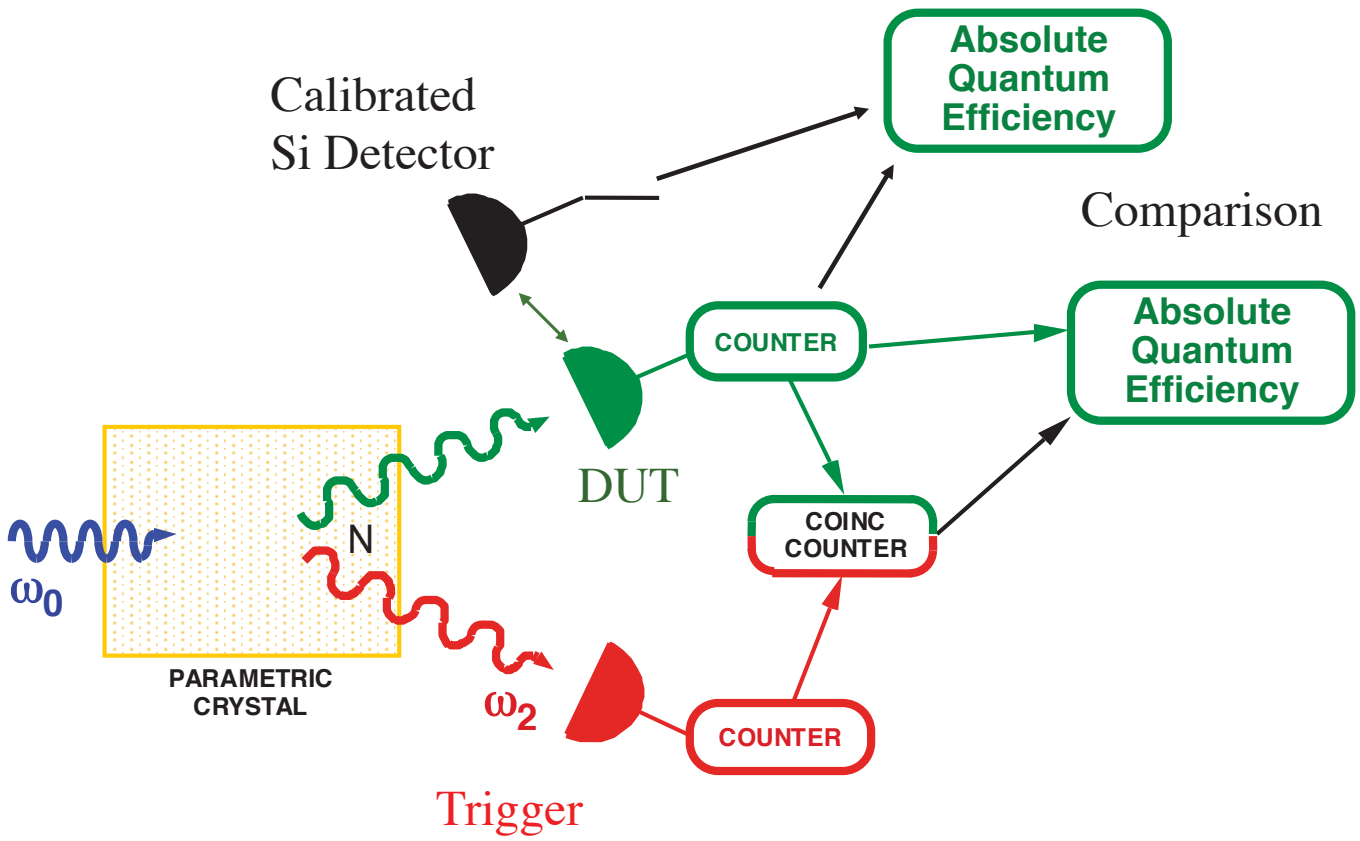
B-field, current, energy → Radiance

Heralded Source

single photons



Verifying the Method

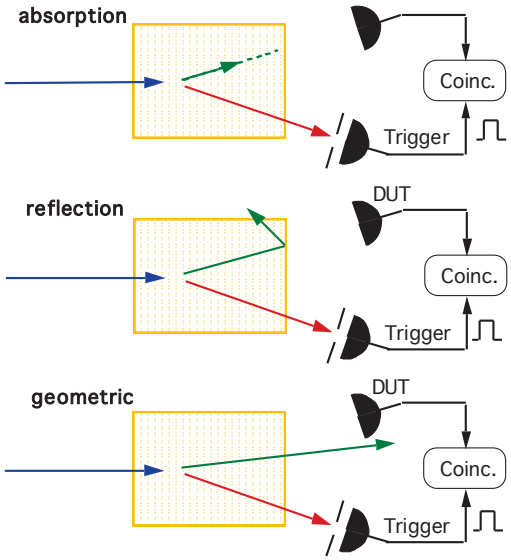


Turning Two-Photon Method into Metrology

Sources of uncertainty:

DUT Collection Efficiencies

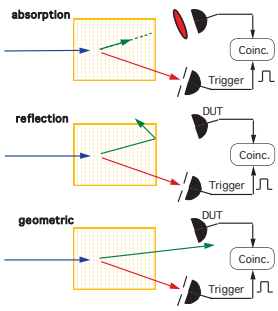
- **Spatial**
- **Angular**
- **Spectral**
- **…**

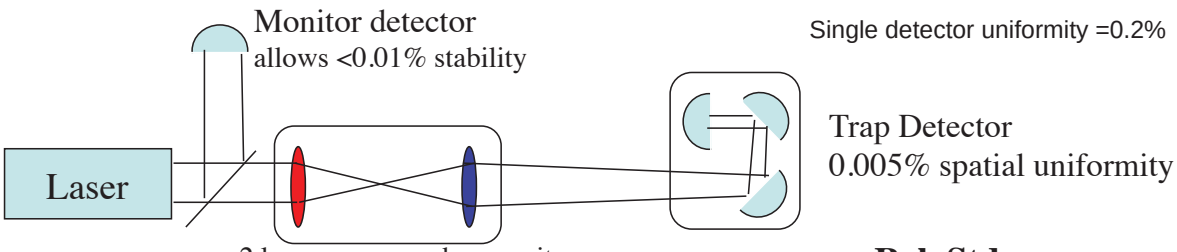


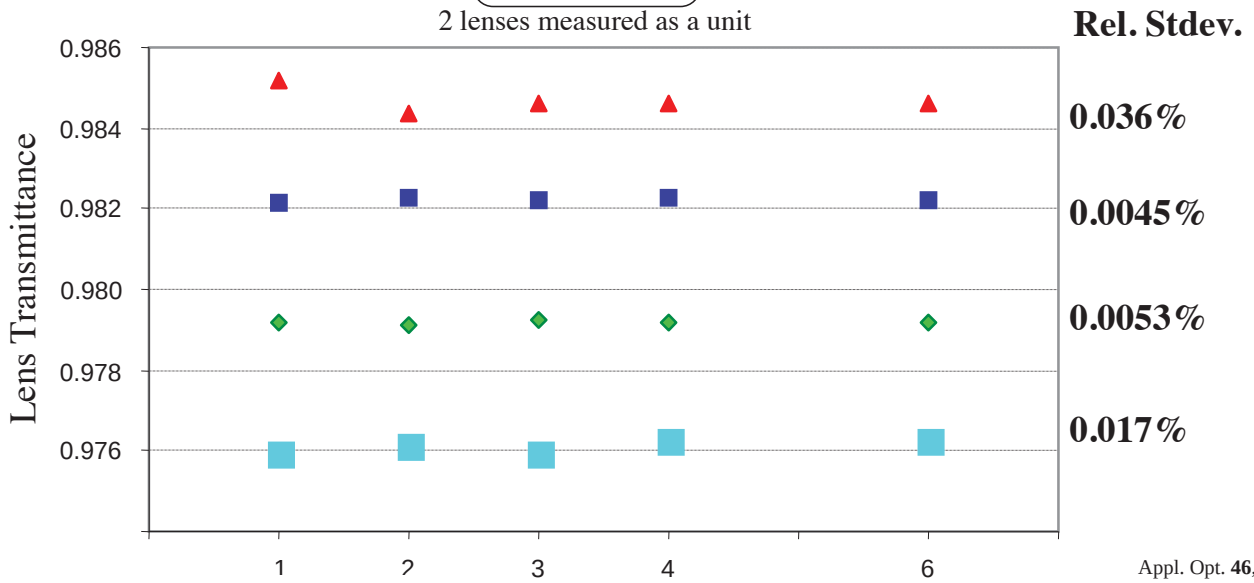
Trigger counting
Coincidence determination

⋮

One Detail: Lens transmittance σ≈0.02%





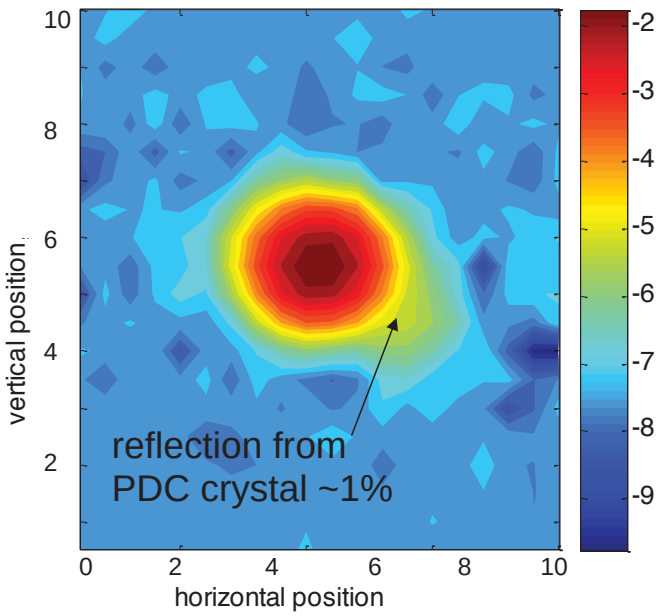


Appl. Opt. **46**, 5396 (2007)

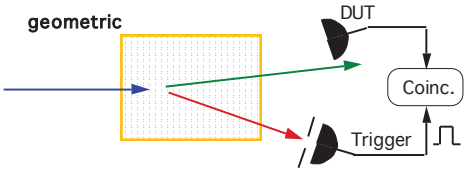
6 measurements of 4 lenses

J. Cheung, NPL

Another detail:
Spatial distribution of correlated photons
(are we missing any?)

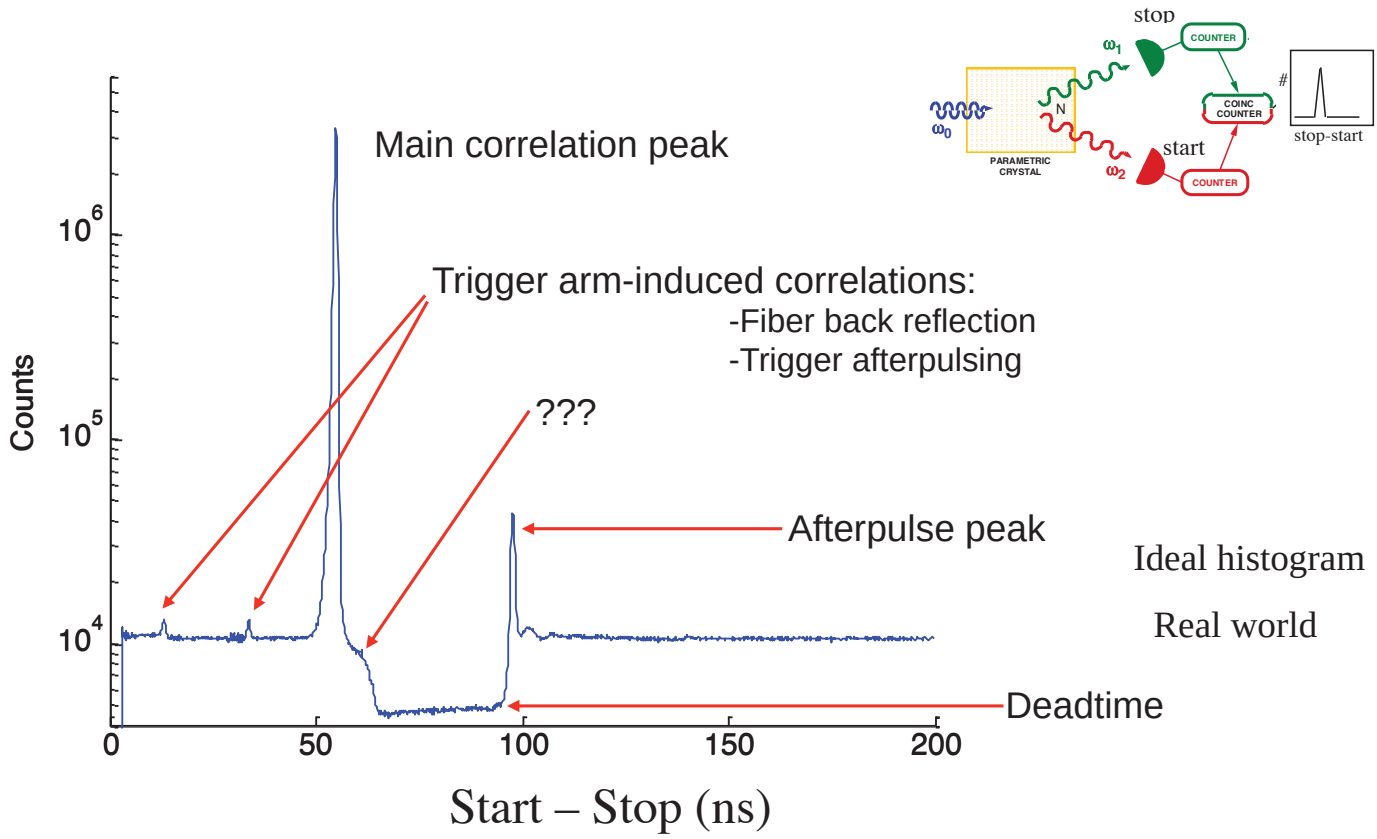


Spatial scan of correlated photon beam

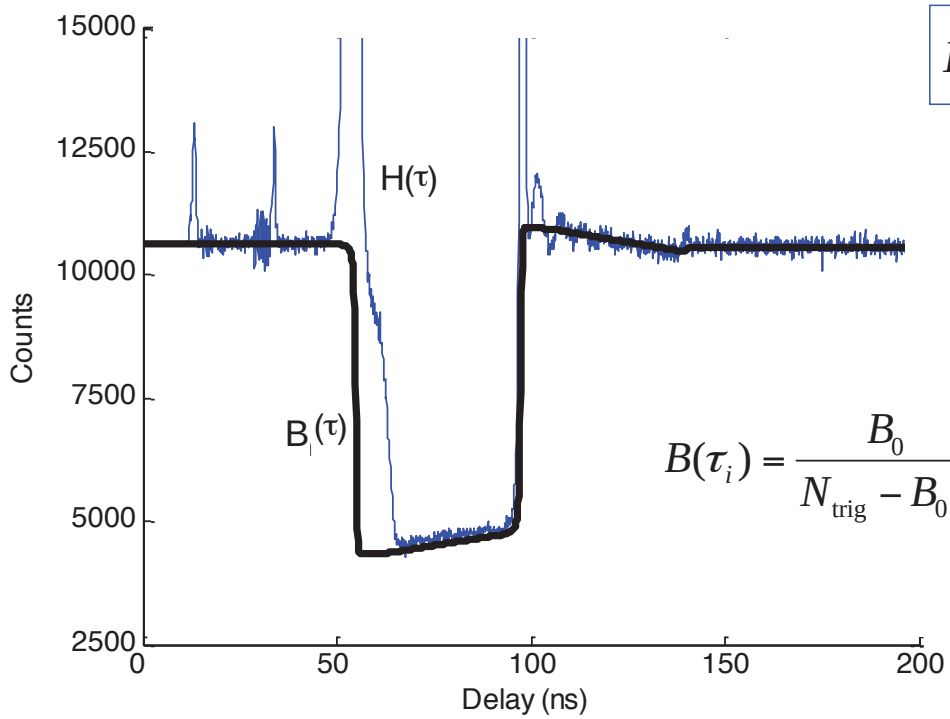


We identify & quantify
any missed fraction

Histogram and its Details



Signal and Background
(we can model it)



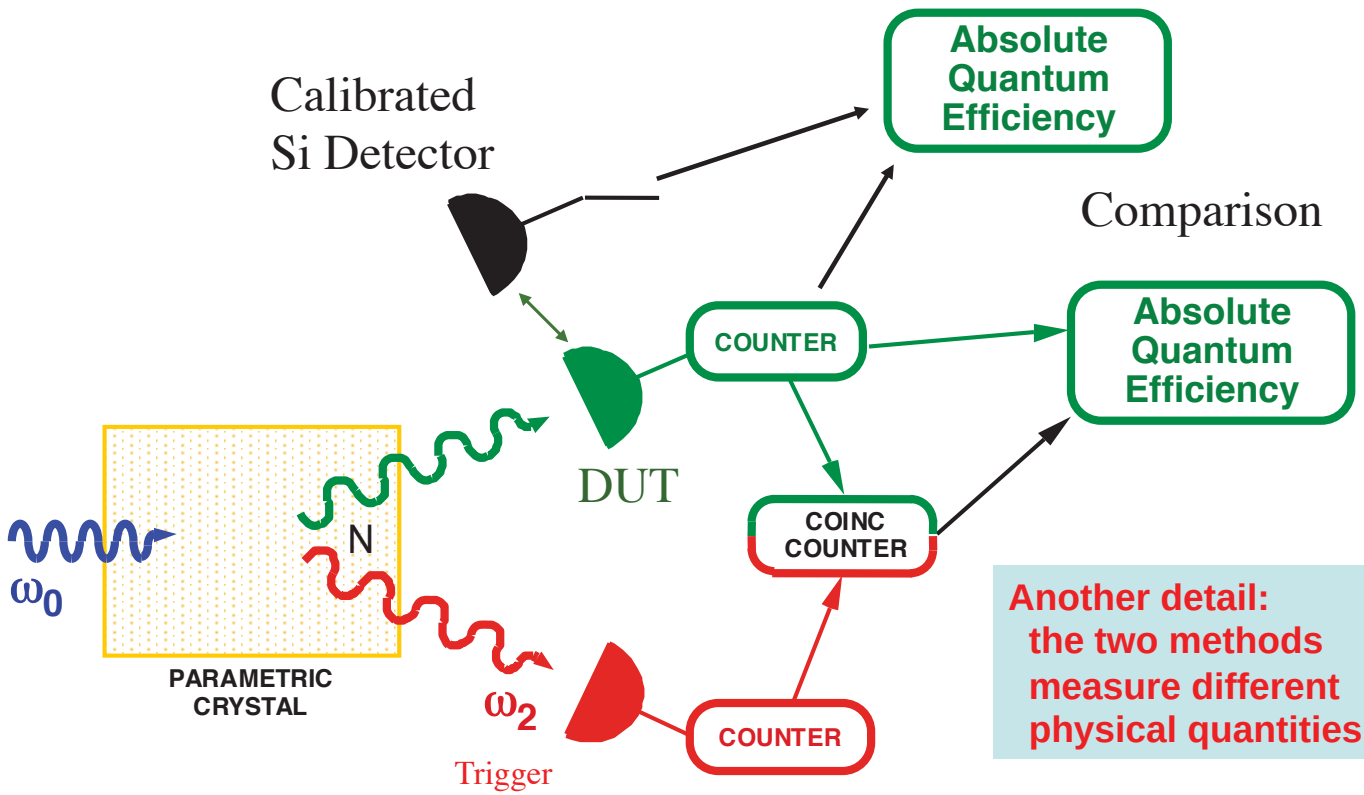
$$H(\tau_i) = C(\tau_i) + B(\tau_i)$$

$$B(\tau_i) = \frac{B_0}{N_{\text{trig}} - B_0 d}\left[N_{\text{trig}} - \sum_{j=i-d}^{i-1} H(\tau_j)\right]$$

Correlated photon calibration method uncertainty budget

Physical property	Value	Relative uncertainty of value (%)	Sensitivity	Relative uncertainty of DE (%)	
Crystal reflectance	0.09249	0.2%	0.1	0.02%	Optical losses
Crystal transmittance	0.99996	0.009%	1	0.009%	
Lens transmittance	0.97544	0.0027%	1	0.0027%	
Geometric collection (raster scan)	0.9995	0.05%	1	0.05%	
DUT filter transmittance	0.9136	0.1%	1	0.10%	
Trigger bandpass to virtual bandpass/ wavelength				0.07%	
Histogram background subtraction				0.03%	Histogram
Coincidence circuit correction	0.0083	10.0%	0.008	0.084%	
Counting statistics				0.08%	
Deadtime (due to rate changes with time)				0.02%	
Trigger afterpulsing	0.0025	25.0%	0.003	0.06%	Trigger
Trigger background, & statistics	175000	0.3%	0.035	0.01%	
Trigger signal due to uncorrelated photons	0	0.07%	1	0.07%	
Trigger signal due to fiber back reflection	0.00202	1.60%	0.002	0.003%	
Total				**0.18%**	

Verifying the Method

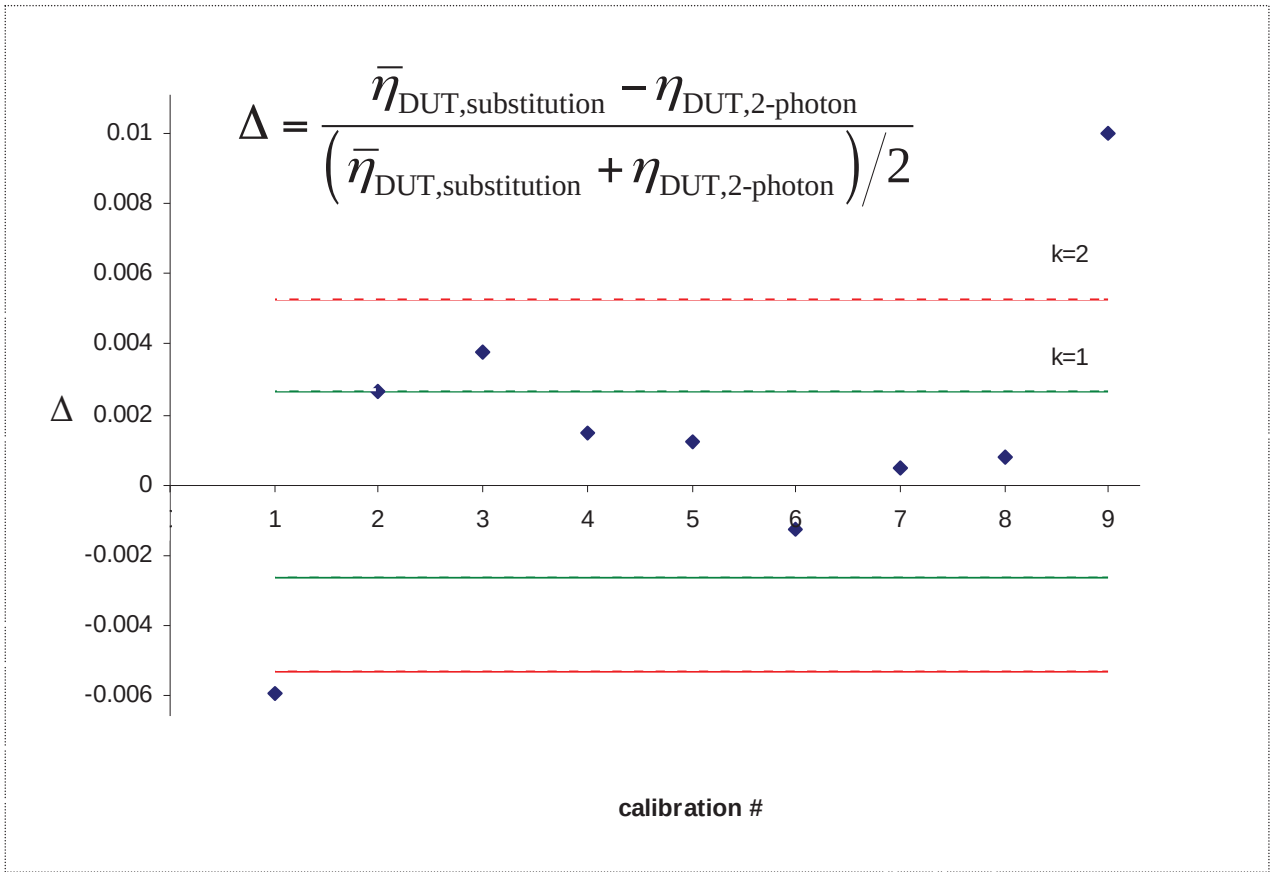


Another detail:
the two methods measure different physical quantities!

Detector substitution calibration uncertainty budget

Physical property	Value	Relative uncertainty of value (%)	Sensitivity	Relative uncertainty of DE (%)
Analog transfer standard calibration (QE equivalent)	0.61906	0.10%	1	0.10%
Spatial nonuniformity at 700nm, (standard deviation of central responsivity)	1	0.025%	1	0.025%
Analog measurement statistics & drift				0.06%
Analog amplifier gain calibration	1.0022	0.050%	1	0.05%
Pinhole backside reflection	0	0.1%	1	0.10%
DUT signal & background statistics				0.003%
DUT afterpulsing	0.00322	11.6%	0.003	0.04%
DUT deadtime (due to rate changes with time)				0.02%
Total Uncertainty				**0.17%**

Agreement Between Methods



Comparison/Results

- NIST implementation of High Accuracy SPD Calibration methods

Method	Absolute uncertainty
Two-photon	0.18%
Substitution	0.17%

- Uncertainty of each individual comparison:

0.25%

- Overall mean difference between the two methods:

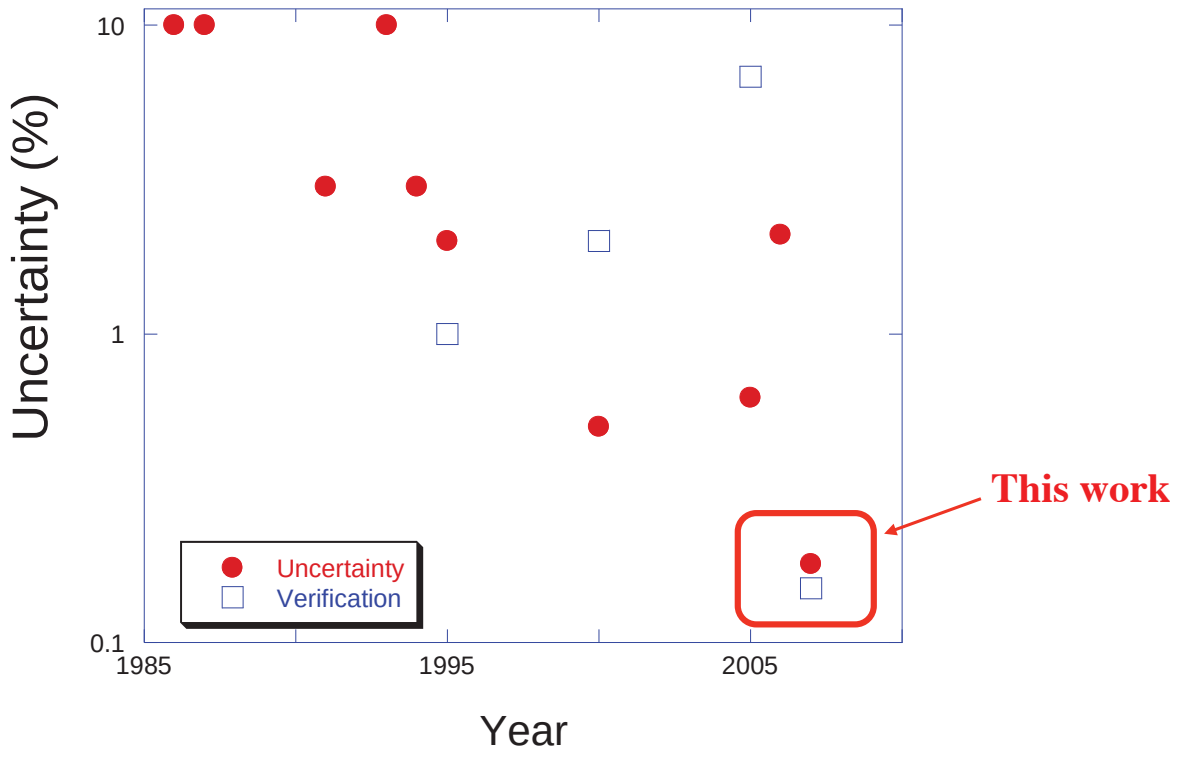
0.15%±0.14% $(\eta_{\text{sub.}} > \eta_{\text{2-photon}})$

Highest accuracy verification of the 2-photon method yet achieved

2-Photon Metrology Progress

Year	1st author	Uncertainty of Method	Uncertainty of Verification	External Comparison
1970	Burnham	~35%		Calibrated lamp
1981	Malygin	-		
1986	Bowman	~10%		
1987	Rarity	~10%		HeNe + attenuation
1991	Penin	> 3%		
1993	Ginzburg	~10%		Published values
1994	Kwiat	~3%		
1995	Migdall	< 2%	1%	Calibrated Si Detector
2000	Brida	~0.5%	2%	Calibrated Si Detector
2005	Ghazi-Bellouati	1.1, 0.62%	6.8%	French cryoradiometer
2006	Wu	2.1%		
2007	Polyakov	0.18%	0.15%	Calibrated Si Detector

Metrology Progress



Beyond Detection Efficiency

- Quantum Statistics for Detection Efficiency
  - Zeldovich and Klyshko, *Field Statistics In Parametric Luminescenc*e, Sov. Phys. JETP Lett. 9, 40-43 (1969)
  - Mogilevtsev, *Calibration of single-photon detectors using quantum statistics*, PRA 82 021807(2010)
  - Worsley, et al. *Absolute Efficiency estimation of photon-number-resolving detectors using twin beams*, Opt. Expr. 17 4397(2009)

- Full Quantum Description of Detector
  - POVM reconstruction – Brida et al.

Beyond Detection Efficiency

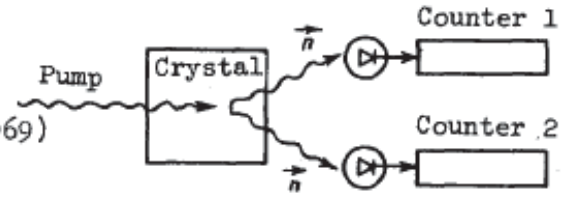
- Original concept proposal:

  N-photon bipartite state correlation

FIELD STATISTICS IN PARAMETRIC LUMINESCENCE

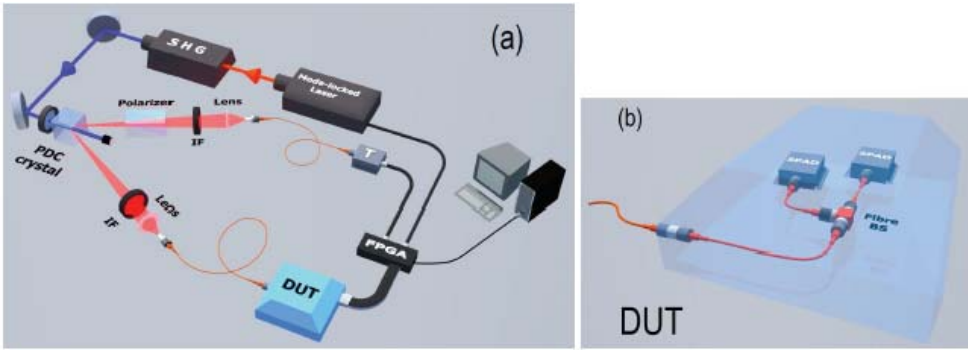
B. Ya. Zel'dovich and D. N. Klyshko

ZhETF Pis. Red. 9, No. 1, 69 - 72 (5 January 1969)



"… can be regarded as an example of a system at whose output there are generated (in direction n) <u>states with a definite number of quanta</u>.
We know of no other proposed system (even hypothetical) for this purpose."

- POVM reconstruction



DUT:
2-detector tree

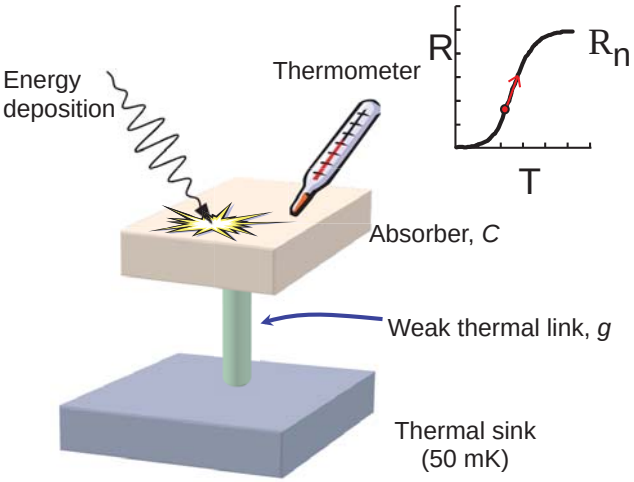
Tomographer:
non-PNR SPAD

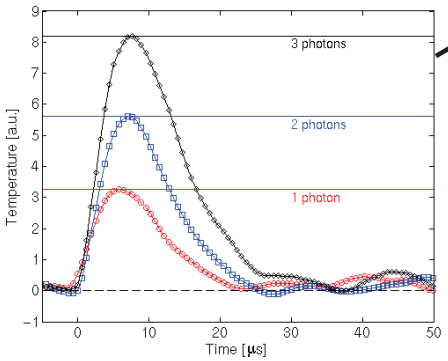
Genovese, Degiovanni, Brida, Ciavarella, Mingolia, Paris, Piacentini INRIM & Polyakov, AM

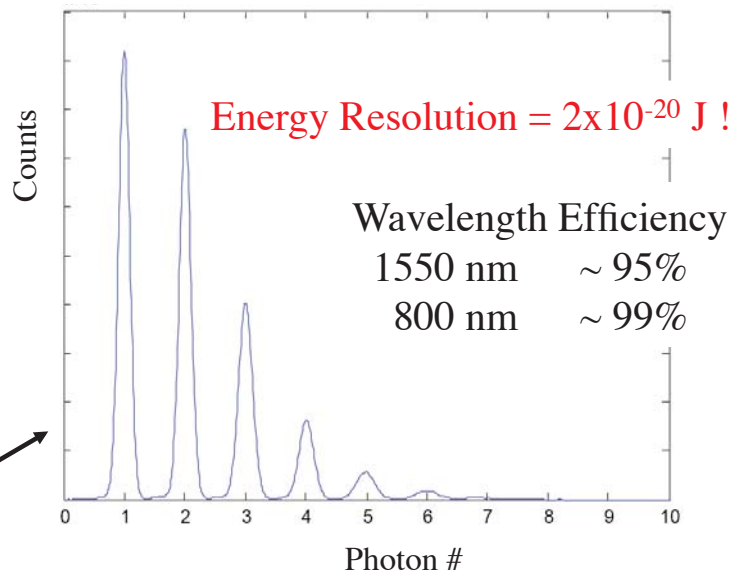
Pushing the limits of Single Photon Counting and Photon Number Resolution

- and our capability to measure it

Transition Edge Sensor (TES) Microbolometer





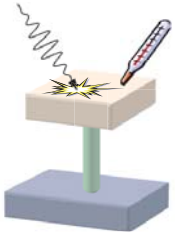


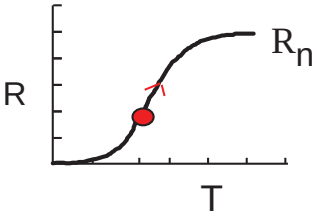
It Can Really Count Photons

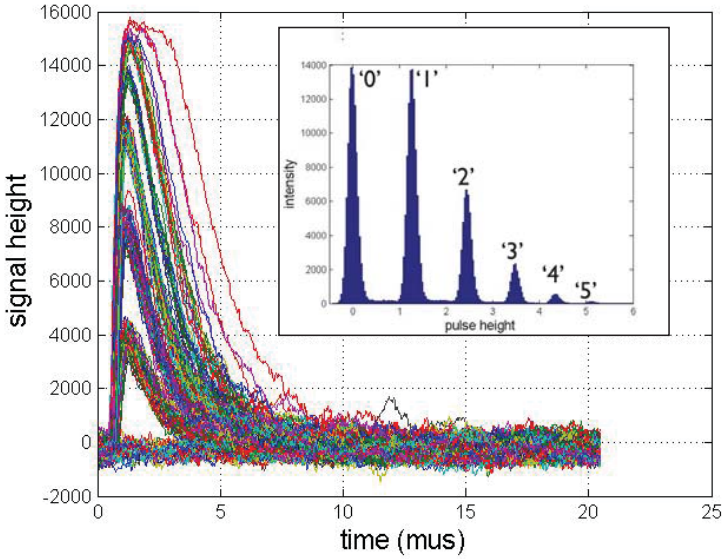
- Optimized now for photon-number resolution, not speed (τ_{rise}~100 ns, τ_{fall}~1 μs)
- Absorption events show good distinguishability
- Much slower than APDs

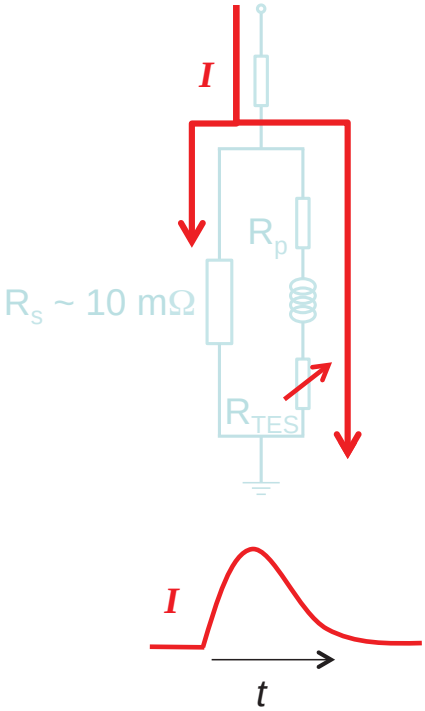
S. Nam

Transition Edge Sensor: pushing the limits

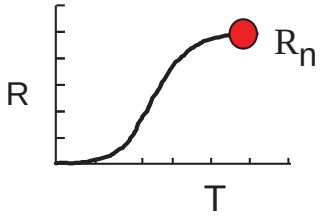


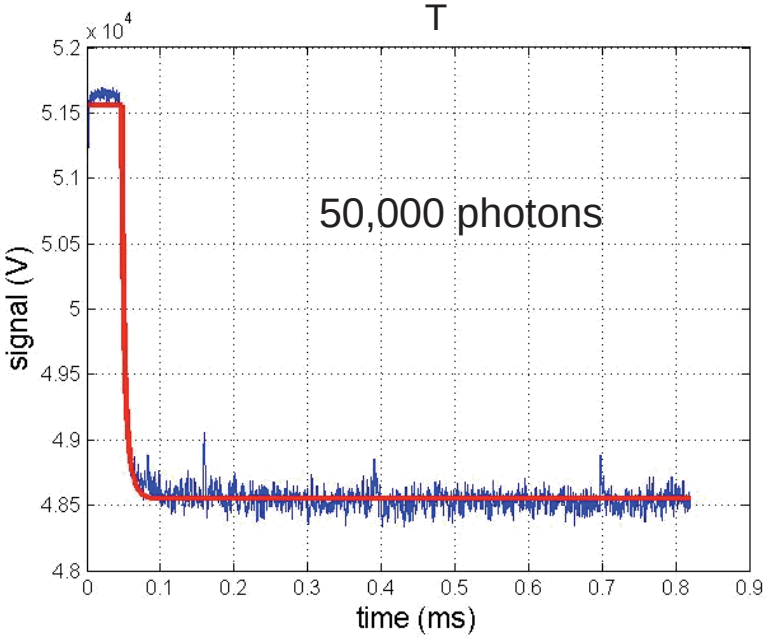


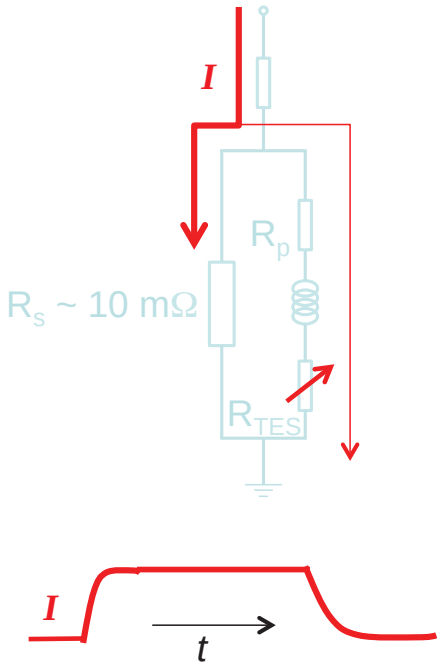




Beyond Single Photon Counting Temporal Traces

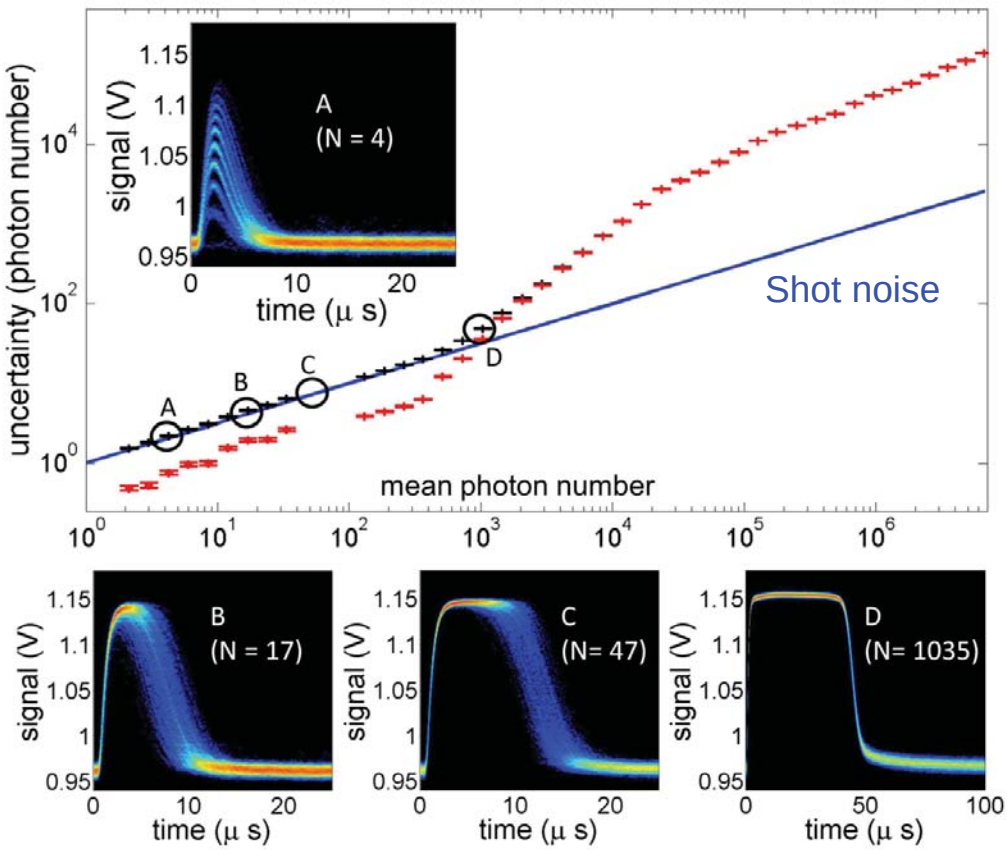






Results so far:

Measured 100 photons
with 3 photons uncertainty
and 94 % quantum efficiency



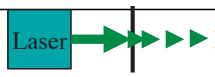
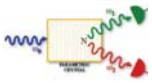
Number Resolution

95% certain @ n=23

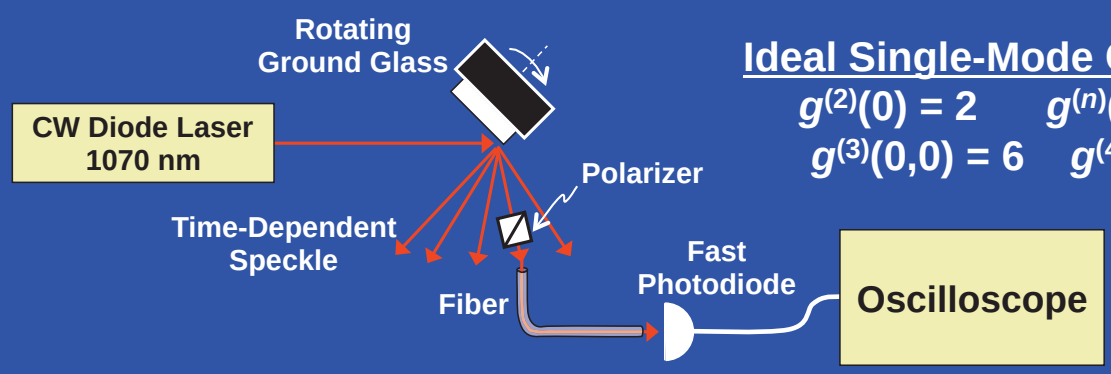
Gerrits
Nam
Calkins
Tomlin
Lita
Mirin
Levine

Source Metrology

Sources

Source type	Prob. or Deter.	Temp. (K)	Wave-length range general	Wave-length tunability specific	Inherent bandwidth	Emission efficiency (Extraction)
Faint laser 	P	300	vis-IR	nm	GHz	1
Two photon (heralded)						
Atomic cascade	P	...	Atomic line	MHz	10 MHz	0.0001
PDC 						
Bulk	P	300	vis-IR	nm	nm	0.6
Periodically poled	P	300–400	vis-IR	nm	nm	0.85
Waveguide (periodically poled)	P	300–400	vis-IR	nm	nm	0.07
Gated	D	300	vis-IR	nm	nm	0.27
Multiplexed	D	300	vis-IR	nm	nm	0.1
FWM						
DSF	P	4–300	IR	nm	nm	0.02
BSMF	P	300	vis-IR	nm	nm	0.26
PCF	P	300	vis-IR	10 nm	nm	0.18
SOI waveguide	P	300	IR	10 nm	nm	0.17
Laser-PDC hybrid	P	300	vis-IR	nm	nm	...
Isolated system						
Single molecule	D	300	500–750 nm	30 nm	30 nm	0.04
Color center (NV)	D	300	640–800 nm	nm	nm	0.022
QD (GaN)	D	200	340–370 nm	nm	nm	...
QD (CdSe/ZnS)	D	300	500–900 nm	nm	15 nm	0.05
QD (InAs) in cavity	D	5	920–950 nm	10 GHz	1 GHz	0.1
Single ion in cavity	D	≈0	Atomic line	MHz	5 MHz	0.08
Single atom in cavity	D	≈0	Atomic line	MHz	10 MHz	0.05
Ensemble						
Rb, Cs	D	10^{-4}	Atomic line	MHz	10 MHz	0.2

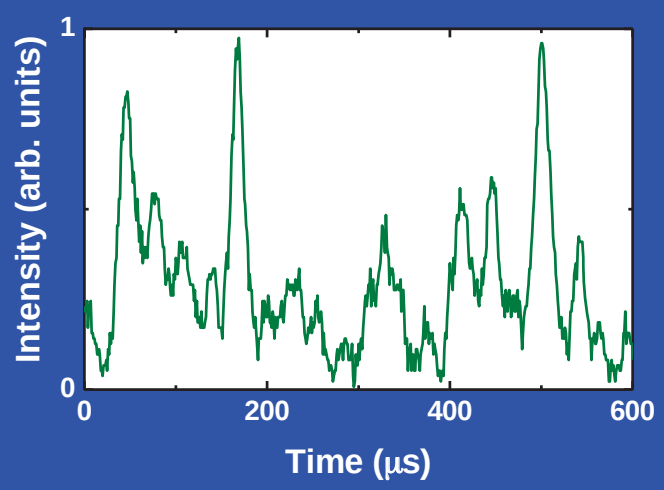
Chaotic, Pseudo-Thermal Source



Ideal Single-Mode Chaotic Source

$g^{(2)}(0) = 2 \qquad g^{(n)}(0,0,\ldots 0) = n!$

$g^{(3)}(0,0) = 6 \qquad g^{(4)}(0,0,0) = 24$



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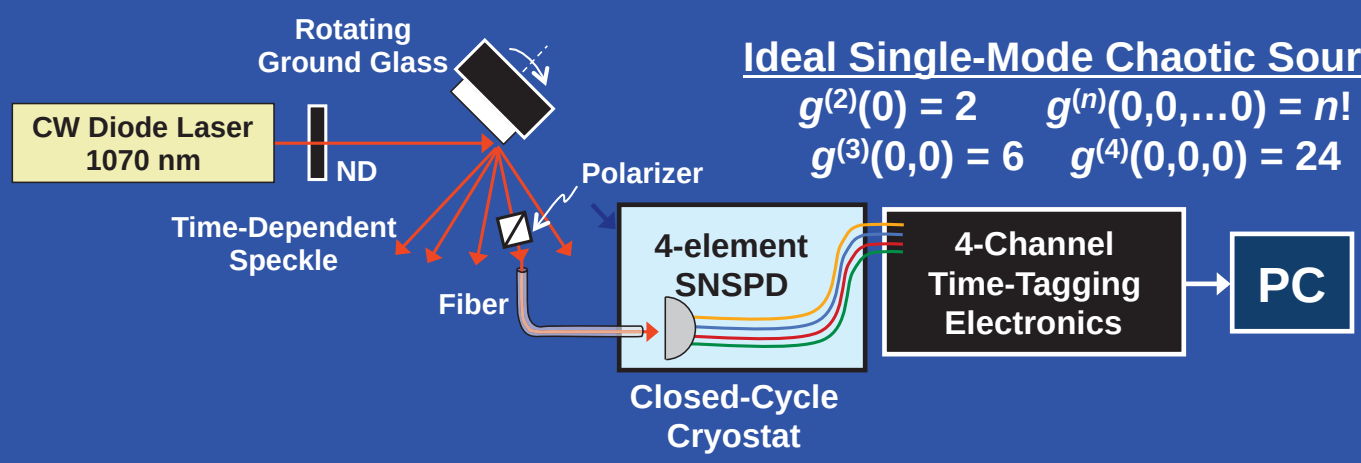
2nd-Order Coherence



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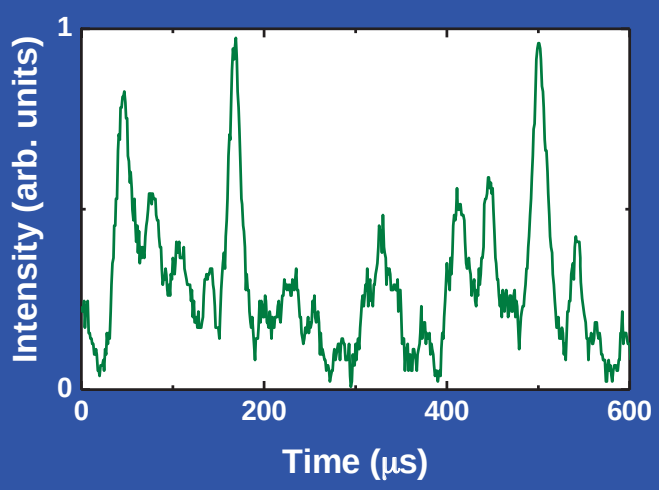

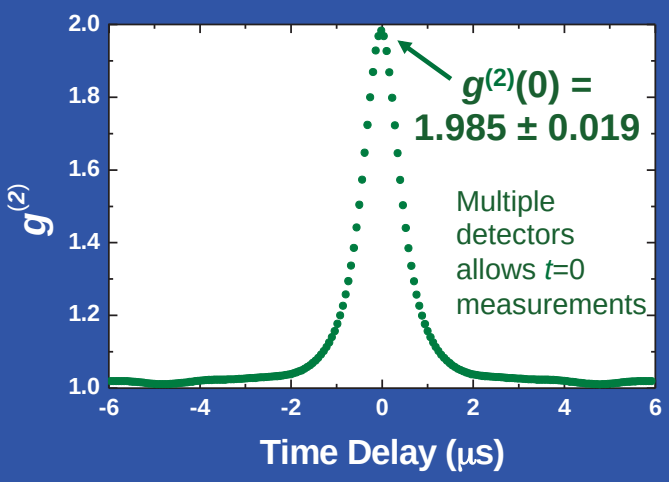

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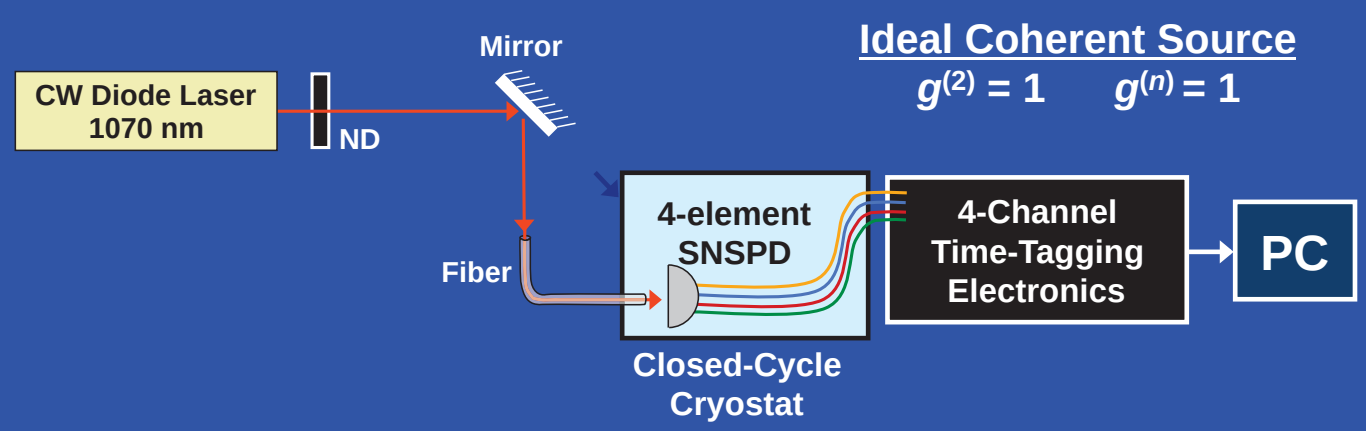
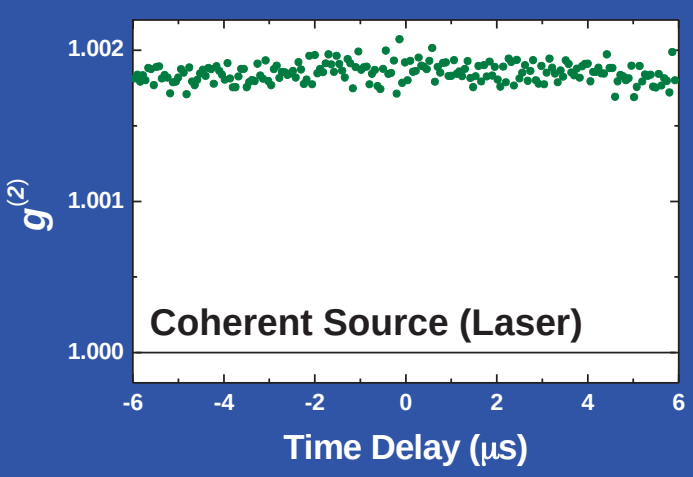
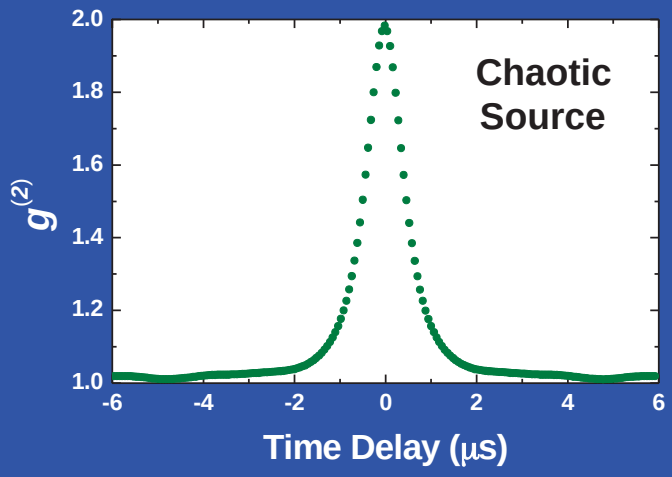
2nd-Order Coherence



Ideal Coherent Source

$g^{(2)} = 1 \qquad g^{(n)} = 1$





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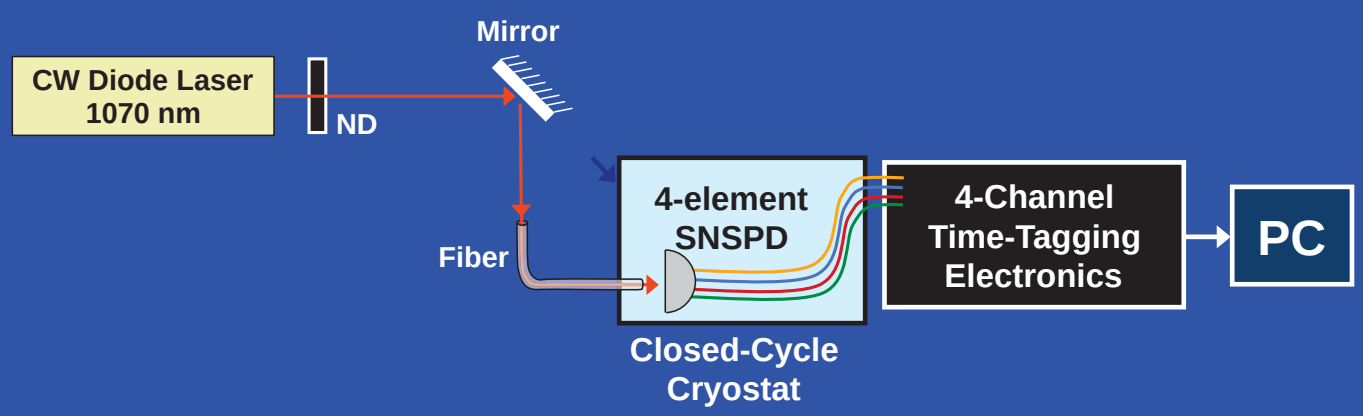
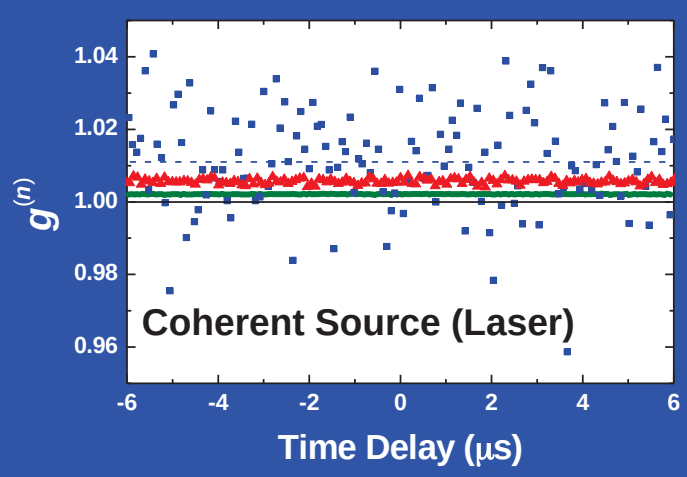
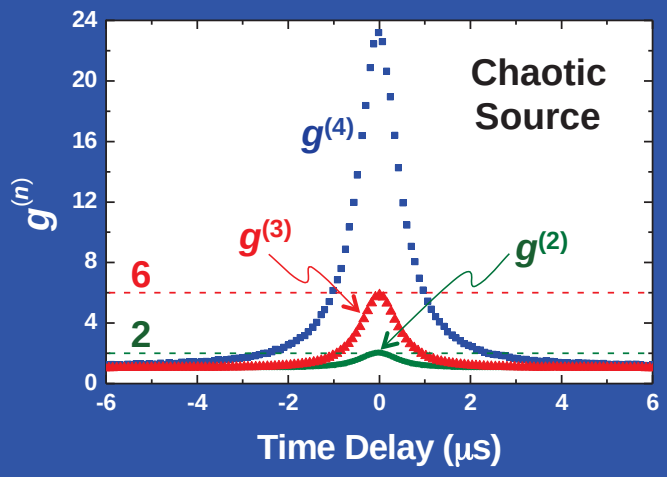
Higher-Order Coherence







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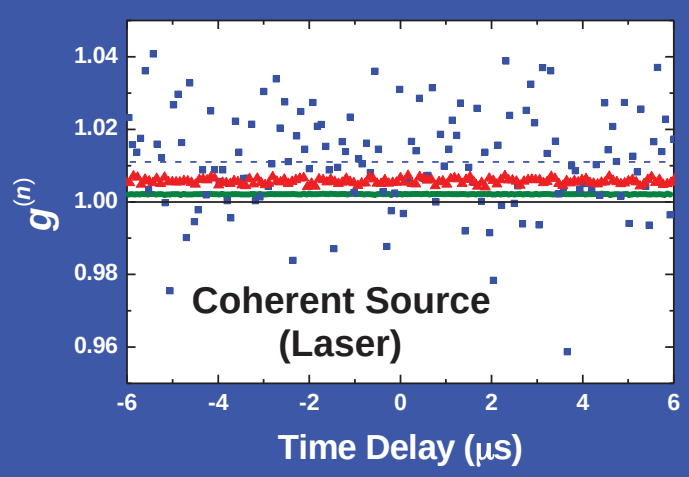
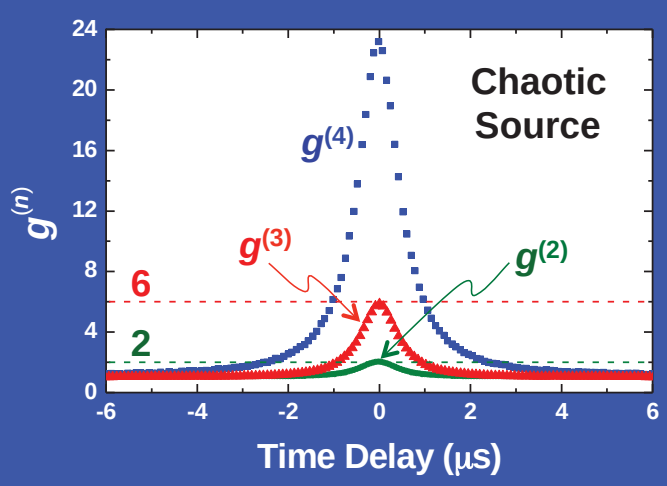
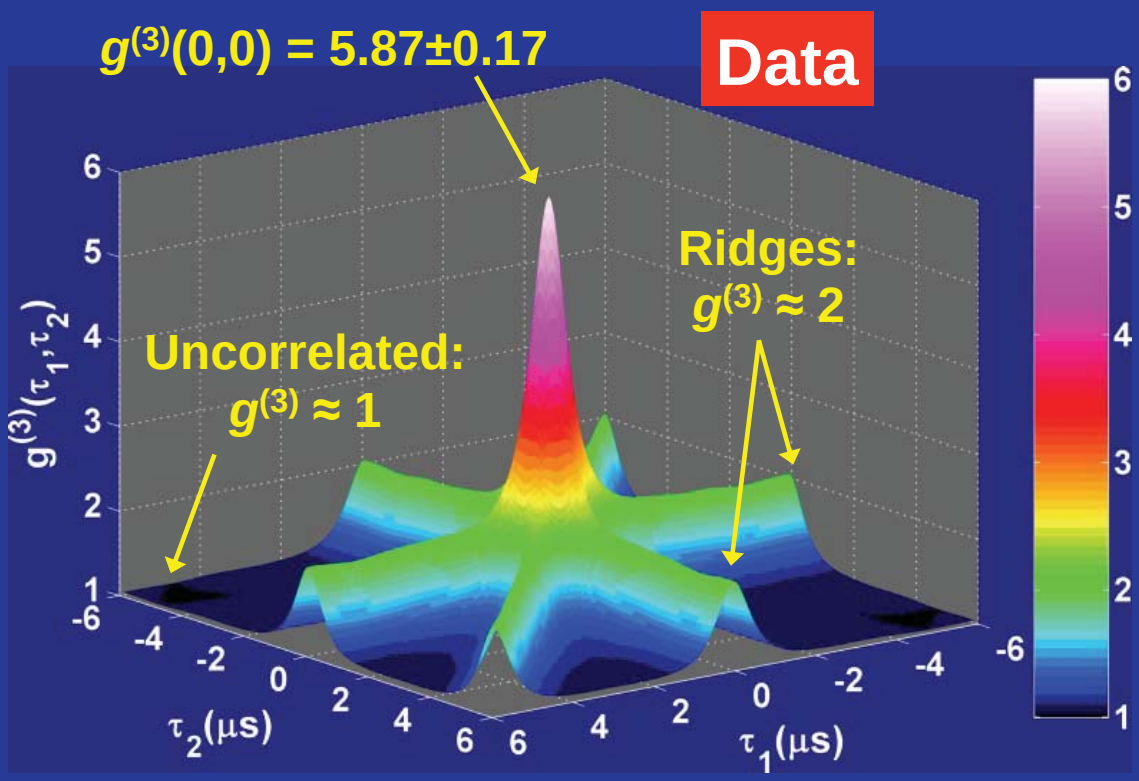
Higher-Order Coherence

	Coherent (Avg)		Chaotic (All $\tau_i = 0$)	
	Expected	Result	Expected	Result
$g^{(2)}$	1	1.0018 ± 0.0008	2	1.99 ± 0.02
$g^{(3)}$	1	1.006 ± 0.002	6	5.9 ± 0.2
$g^{(4)}$	1	1.011 ± 0.005	24	23 ± 2





3rd-Order: Chaotic Source



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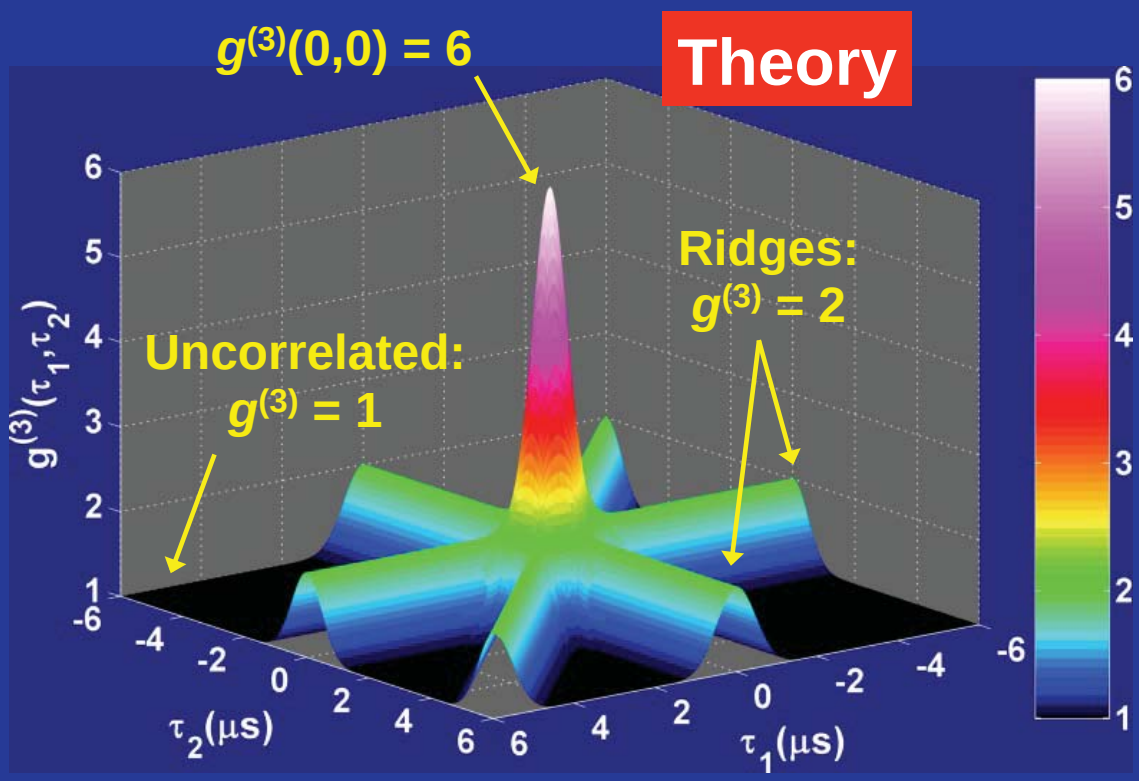
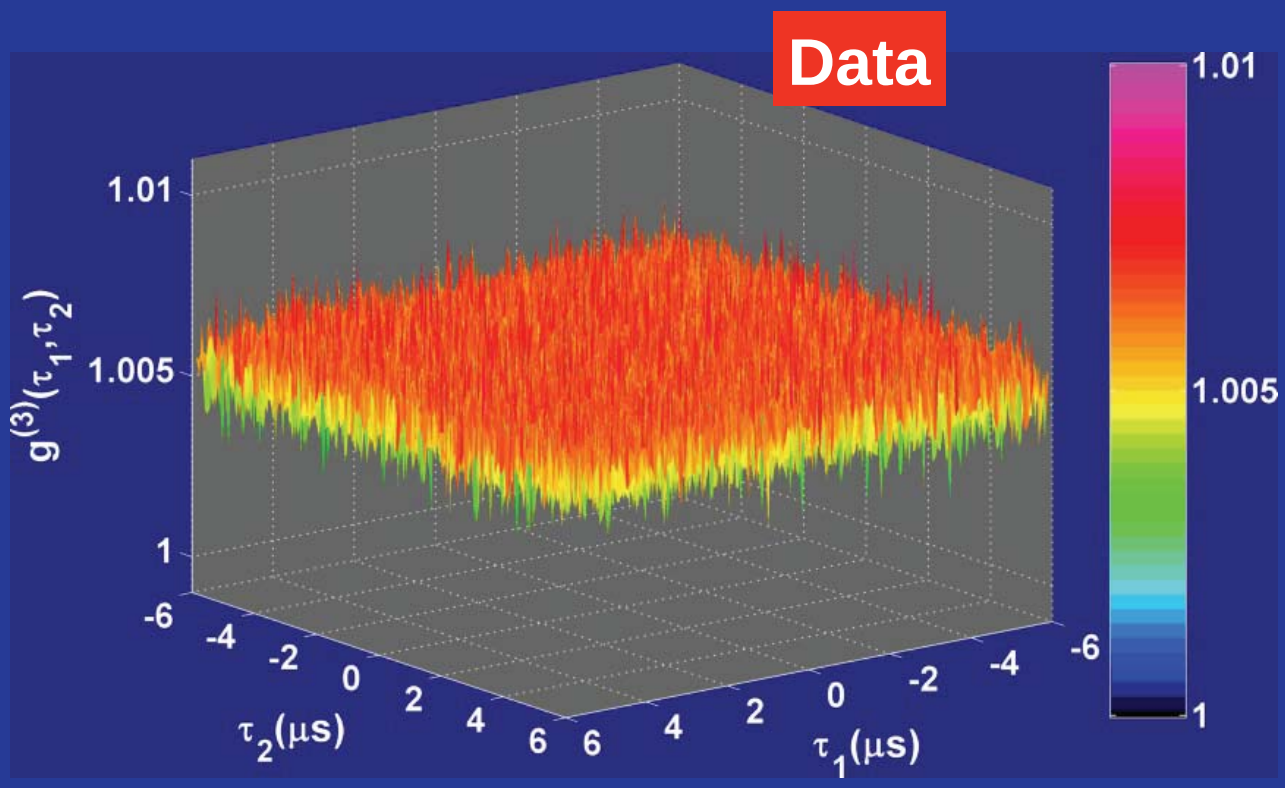
3*rd*-Order: Chaotic Source



Calculation assumes ideal Gaussian scattering process:
P.-A. Lemieux and D. J. Durian, *JOSA A* 16, 1651 (1999)

3rd-Order: Coherent Source



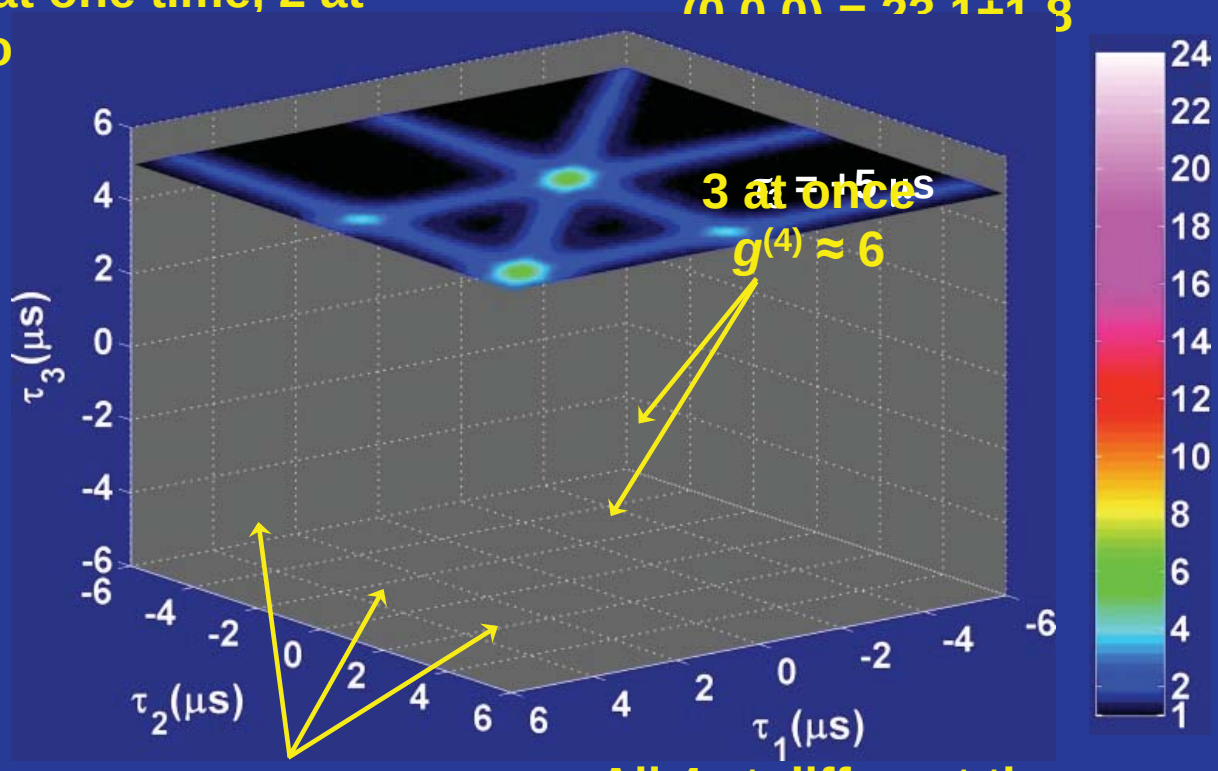
Mean value: $\langle g^{(3)} \rangle = 1.006 \pm 0.002$

→ Precision measurement of weak cross-correlation

4th-Order: Chaotic Source

2 at one time, 2 at ano

All 4 at once: $g^{(4)}$ (0,0,0) = 23.1±1.8



3 at once
$g^{(4)} \approx 6$

2 Elements fire simultaneously
$g^{(4)} \approx 2$

All 4 at different times
$g^{(4)} \approx 1$

Single-Photon Metrology

- Detection Efficiency Status: 0.1% uncertainty
- Beyond single parameter characterization: POVM
- Single Photon Detection reaching upwards:
  - TES: 20 to 1000 to 10^6
  - Max count rates to 10^9
- Single Photon Sources reaching upwards: 10^9 /s
- Conventional radiometry reaching downwards:
  - 1000 photons/s

- Single Photon radiometry: holds promise of moving radiometry to counting problem
- Efficiencies remain an issue